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APPARATUS FOR THE MEASUREMENT OF AIR BLAST PRESSURES BY MEANS OF PIEZOELECTRIC GAUGES

by

G. K. Fraenkel

The Underwater Explosives Research Laboratory
Woods Hole Oceanographic Institution

NDRC Report No. A-373
OSRD Report No. 6251

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NDRC Report No. A-373
OSRD Report No. 6251

Submitted on March, 1946 by

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Preface

The work described in this report is pertinent to War Department Project OD-03, "Study of Shock Waves" and to Navy Department Project NO-283 "Air-Blast Measurements." The report constitutes a progress report under Contract OEMsr-569 with the Woods Hole Oceanographic Institution, and is one of the final reports of this contractor. It was prepared as a part of task A under Contract NOrd-9500 with the Bureau of Ordnance, under which this laboratory has continued its work.

E. Bright Wilson, Jr.
Chief, Division 2, NDRC

Paul C. Cross
Research Director, UERL
(for Contract OEMsr-569)

Personnel

The work described in this report has been carried out by a number of people during the last three and one-half years. It was begun at Harvard University by E. B. Wilson, Jr. and D. F. Hornig.

The work has been continued at the Underwater Explosives Research Laboratory under the general supervision of W. D. Kennedy; G. K. Fraenkel has been in charge of the electronics development and maintenance; other electronics personnel include C. W. Tait, H. P. Field, and R. S. Kuhn; wiring was done by Nancy Sisson and E. W. Olmsted. R. F. Arentzen and W. E. Curtis were engaged in the non-electronic aspects of the work, including the operational use of the apparatus. R. H. Cole and David Stacey assisted in frequent consultation.

Paul C. Cross
Director of Research
(Contract OEMsr-569)

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Abstract

For the purpose of measuring the peak pressure and positive impulse in the air-blast from high explosives, the apparatus used should fulfill certain requirements in order to ensure the accuracy of the results. These requirements are given in detail, and the apparatus which was devised, constructed and used by the Underwater Explosives Research Laboratory for air-blast measurements by means of piezoelectric gauges is described.

The apparatus makes use of cathode-ray oscillographs by means of which the amplified output pulses from piezoelectric gauges are recorded in permanent form by cameras. The units of the apparatus which perform the calibrations of the deflections on the oscillograph screen in terms of voltage and time are described. Cameras of two types, one involving fixed film, which necessitates the use of an electronic sweep-generator, the other using moving film, are described. The circuit diagrams for all units of the apparatus, including amplifiers, power supplies, timing units, master controls, and so forth are given and discussed.

Cathode-ray oscillographs of two types were used: in one type of apparatus, the DuMont type 208 oscillograph was the basic unit; in another, an eight-channel oscillograph which was especially designed for the purpose was used. A mobile laboratory, housed in a semi-trailer, and equipped with the apparatus necessary for air-blast measurements on bombs and charges of many types and sizes is described.

The technique of measuring the shock-wave velocity, from which the peak pressure may be calculated, is described. The equation which relates the pressure to the velocity is presented and the application of the method in practice is discussed.

Some discussion is given of the apparatus used for supporting gauges and charges, and of the experimental procedures which have been found useful in field work.

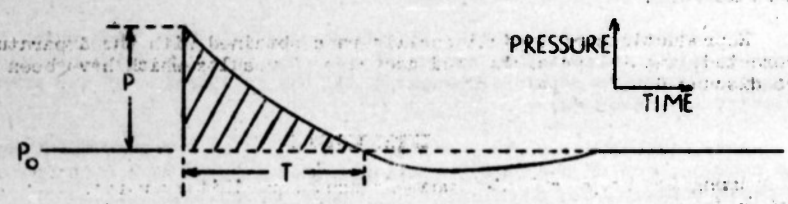
Reproductions of typical oscillograms obtained with the apparatus are presented, and the precision and accuracy of results which have been obtained are discussed.

INTRODUCTION

Among the many explosive weapons used for military purposes, a large number depend for their effectiveness on the blast wave produced in the air by the detonation of the explosive. This pressure wave is responsible for a considerable part of the damage produced by aerial bombing with high explosives to structures such as factories, dwellings, fortifications, and ships, as well as the effectiveness of explosives in the clearance of minefields. A knowledge of the properties of blast waves is used in evaluating the damage caused by explosions in order to design more efficient explosives and explosive devices, to plan tactical uses of explosives, to develop structures capable of withstanding the effects of blast, to determine the danger of blast to friendly personnel, to design explosive storage igloos, and so forth.

A large quantity of energy in the form of heat and light is liberated by the detonation of a high explosive; gases are produced at a high temperature and pressure, and a pressure wave, known as a shock wave, is sent out into the surrounding medium from the center of the detonation. A shock front is a discontinuity of pressure which is believed to occur within an interval of the order of molecular dimensions. In addition to the pressure discontinuity, a shock front is accompanied by an elevated temperature and by motion of the air which, together with the velocity of the shock, are related to the shock pressure.

The pressure in the shock wave is a function of the distance from the charge and, at a fixed distance, is a function of time. At fixed distances (greater than a few charge radii from the detonation) the pressure in the shock front rises to its "peak" value in a time which is effectively instantaneous, decays gradually with time until it reaches a minimum, which is below atmospheric pressure, and then returns slowly to atmospheric pressure. Figure 1 is an idealized plot of this type of pressure-time curve at a fixed distance from the detonation of a high explosive in air.



P_o = ATMOSPHERIC PRESSURE
P = SHOCK WAVE PEAK PRESSURE
T = POSITIVE DURATION

FIG. 1. PRESSURE VERSUS TIME AT A FIXED DISTANCE FROM THE DETONATION OF A HIGH EXPLOSIVE IN AIR.

The maximum value of the pressure in the shock wave in excess of atmospheric will, for the purposes of this report, be called the peak pressure, and the time required for the positive pressure to decay to atmospheric pressure will be termed the crossing time or positive duration. Referring to Fig. 1, the shaded area bounded by the positive part of the pressure curve and the axis of atmospheric pressure, $\int_0^T p(t)dt$, is called the positive impulse or positive momentum. The parameters ordinarily used in characterizing blast waves are the peak pressure, the positive impulse, and the positive duration; of these the positive duration is probably the least important.

The peak pressure has very high values close to the center of the explosion and decreases to zero (that is, atmospheric pressure) at large distances. The positive impulse is believed to have a low value close to the explosion, increases to a maximum and then decreases with increasing distance [1].* The positive duration is thought to increase with distance from an initially small value. For spherical or cylindrical charges these parameters can be expressed approximately, as functions of charge weight and distance, by the following equations:

$$P = A \left(\frac{w^{1/3}}{r}\right)^n \tag{0.1}$$

$$\frac{I}{w^{1/3}} = B \left(\frac{w^{1/3}}{r}\right)^m \tag{0.2}$$

$$\frac{T}{w^{1/3}} = C \left(\frac{w^{1/3}}{r}\right)^\ell \tag{0.3}$$

where P = peak pressure (in excess of atmospheric pressure) (lb/in^2)
I = positive impulse ($lb\text{-}msec/in^2$)
T = positive duration (msec)
w = charge weight (lb)
r = distance from charge (ft)
A, B, C, ℓ, m, and n are constants which depend on the nature of the charge, the pressure region and the conditions of measurement. They are to be regarded as constants only over relatively small ranges of $w^{1/3}/r$.
(The units in parentheses are those most commonly used.)

The exponent n in Eq. (0.1) varies from about +1.5 in the lower pressure region (ca. 0.1 lb/in^2) to about +3 at high pressure levels. In general it is somewhat greater for measurements made close to the ground than for measurements in "free air" and appears to be higher for heavily cased charges than for bare charges. The factor A in Eq. (0.1) depends on the nature of the explosive, the location and the shape of the charge, and the weight of

*All numbers in brackets refer to the List of References at the end of this report.

its case. The value of A for bare cylindrical charges in free air is about 250 (in the units given above) in the region of pressures from 1.5 to 15 lb/in² [1]. It is smaller for cased charges than for bare charges.

The exponent m in Eq. (0.2) is usually less than +1 and, according to theoretical predictions, is negative near the charge. Both m and B are affected by the same variables which affect n and A. The value of B is about 80 (in the units given above) for bare charges on the ground in the region of pressures from 1.5 to 20 lb/in². The exponent γ in the equation for the positive duration [Eq. (0.3)] is negative and quite small at very low pressures and increases to larger negative values at somewhat higher pressures.

The velocity of propagation of the shock front decreases from supersonic velocities at high pressures to the velocity of sound at low pressure; and the particle velocity behind the front decreases from speeds well in excess of the speed of sound (at high pressures) to zero at zero excess pressure. The temperature of the air behind the shock is also very high at high pressures and decreases to the temperature of the atmosphere as the excess pressure approaches zero.

Ordinarily the pressure region in which measurements are made depends on the use of the weapon or explosive being investigated. The largest number of pressure measurements have been made in the range from 3 to 20 lb/in², which is the range most important in consideration of blast damage to urban structures. With weapons intended for use in mine clearance, measurements have been made up to pressures of 150 lb/in², and investigations at much higher pressures are still required. Investigations of the anti-personnel effects of blast and the effect of blast on fortifications and explosive storage magazines also necessitate measurements at high pressures, while for special purposes pressures below 0.02 lb/in² have been recorded.

The size of charges on which tests are made varies from very small charges, used because of their convenience, to full scale service weapons. Cylindrical and spherical charges of less than 1 lb are not ordinarily studied, but equipment similar to that described in this report has been used to measure the blast from charges as large as 20,000 lb, and mechanical gauges have been used to study 250,000 lb charges. Undoubtedly an atomic bomb, or the approximately equivalent 20,000-ton TNT charge, would be the largest charge of interest at the present time.

Not all pressure-time curves have the idealized appearance depicted in Fig. 1, which represents the blast wave from a bare, or uncased, charge in free air. A record from a cased charge would include, superimposed on the main curve, small irregular pressure waves which arise from the fragments that fly out from the explosion at average velocities which, in the region of pressures usually of interest, are in excess of the average shock wave velocity. Multiple peaks, that is, sharp discontinuities of pressure similar to the initial peak, occur on records made off the ends and corners of charges, in measurements on unsymmetrical charges, and in recording reflections from the ground or other obstacles. The occurrence of a secondary peak (much smaller than the primary peak) in the negative region of the pressure-time curve, is quite common. The pressure-time curves recorded by blast gauges at pressures above 20 or 30 lb/in.² are very irregular compared to the relatively smooth curves at lower pressures. The pressure in the positive region of the pressure-time curve decays linearly with time at pressures below about 6 lb/in.², but at higher pressures it tends to approximate a negative exponential curve.

The pressure curve from an explosion in an enclosed space is quite different in nature from that in the open air. It contains a large number of reflections from the walls of the enclosure and consequently the disturbance lasts for a much longer time than for a similar explosion in the open.

Different investigators have studied many of the properties of blast waves [1]. The most extensive work has been concerned with the comparison of different explosives, but investigations have also been made of the physical variables which affect the blast wave, such as the charge weight, the distance from the charge, the height of the charge above the ground, the nature and weight of the case surrounding the explosive, the shape and orientation of the charge, the atmospheric pressure (that is, altitude), and so forth. In addition, studies have been made of the blast in enclosed spaces, of the effect of obstacles and barriers, and of the blast from guns and from slow-burning explosives (SBX). Almost all the investigations which have been carried out to date were made during World War II and were intended to provide an answer to particular military problems; consequently a great many of the fundamental properties of blast waves still remain to be studied.

The equipment described in this report is used for the recording of pressure-time curves from explosions in air. These instruments, the development of which started on a small scale in August 1942 at Harvard University, are designed to be used with tourmaline piezoelectric gauges. The component parts of the blast-recording apparatus are discussed in detail; and this discussion is followed by a description of the two complete units now in use at UERL. Considerable attention is paid to the requirements of different types of equipment for measuring air blast, with particular emphasis on apparatus used in conjunction with piezoelectric gauges. The determination of pressure from measurements of the velocity of propagation of the shock front is also discussed.

Chapter 1

EXPERIMENTAL METHODS FOR THE MEASUREMENT OF BLAST WAVES IN AIR

Investigations of the properties of explosions in air are made by recording the pressure-time curve or the parameters of the pressure-time curve, such as the peak pressure and positive impulse, by photographic studies of the shock wave and fragment distributions, by measurements of ground shock, by measurement of the displacement, strain and damage produced on structures, and by studies of detonation phenomena. The techniques for measuring the blast parameters involve the use of mechanical and electrical gauges. The pressure can also be determined by measurement of the shock-front propagation velocity.

Mechanical gauges are used in the measurement of air blast, although these gauges, which are much simpler than the electrical systems, have not been developed to the point where pressure-time curves can be recorded with adequate fidelity. Mechanical gauges are discussed in Ref. [2] and [3]. A summary of photographic methods is given in Ref. [1]. These techniques will not be described in this report.

The absolute pressure in a shock wave can be determined by measuring the velocity of propagation of the shock. This method depends on the theoretical relation between propagation velocity and pressure which is derived from the Rankine-Hugoniot conditions. These conditions are based only on the conservation of mass, momentum, and energy across the shock front and on the properties of the medium. This method is of considerable importance because the determination of pressure can be made without introducing a disturbance in the region of measurement due to the presence of a recording instrument of finite size. The method of measuring shock velocities is described in detail in Appendix A.

Only the electrical methods for recording pressure-time curves will be discussed in this chapter. All systems for this purpose have certain common characteristics which include: (1) a pressure-sensitive pickup or gauge; (2) a means of transmitting the gauge signal to the recording station either directly, after amplification, or by means of a modulated carrier wave; (3) amplifiers, detectors, and so forth at the recording station; (4) a recording instrument such as a cathode-ray tube; (5) a time base; (6) a camera or other device for obtaining a permanent record of the pressure-time curve.

The general requirements which electrical methods of measuring pressure-time curves must fulfill and a brief comparison of the more important electrical systems will be discussed in the following. The requirements of equipment for the study of blast in enclosed space are somewhat different from those given here [4].

1.1. Requirements of a blast-measuring system

The requirements imposed on equipment for measuring air blast are governed primarily by the size and nature of the charge and by the range of pressures to be measured. It is not always practical to use one set of equipment for measurements on large and small charges because: (1) there is considerable difference in frequency-response requirements and (2) the problems involved in the location of the equipment are quite different.

(a) Sensitivity. — The sensitivity of the measuring system must be sufficient to respond to the lowest pressures encountered, and a means of reducing the sensitivity is necessary in order to record the highest pressures to be measured. The range of pressures which have been measured at this laboratory extends from 0.02 lb/in.² to 150 lb/in.², although a few measurements have been made at about 700 lb/in.² Specialized applications will probably require more detailed study of the high pressure regions than has hitherto been undertaken.

The sensitivity of the recording equipment must be constant during the intervals between sensitivity calibrations. In many cases, although only infrequent calibrations of the pressure-sensitive pickup are made, the rest of the apparatus is calibrated immediately before and after each experiment.

(b) Linearity. — The system should be linear, usually within 1 percent, over the entire region for which it is designed. Non linearity occurring under dynamic conditions is discussed in Sec. 1.1(f).

(c) Freedom from hysteresis. — The system must also be free from hysteresis, that is, its sensitivity should be independent of its previous history.

(d) Frequency-response characteristics. — The response of the recording equipment should be uniform over all the important frequencies which make up the frequency spectrum of the transient pressure signal; these are primarily a function of the charge weight and the pressure level. In the measurement of transient phenomena it is more logical to consider the transient response of the electrical and mechanical components of the recording system rather than the more conventional steady-state sinusoidal response [33]. A function in which the pressure decays linearly with time at the same rate as the decay in the initial portion of the pressure-time curve is used as a mathematical representation for determining the high-frequency components of the pressure-time curve. The function

$$P = P_o \left(1 - \frac{t}{\phi}\right) \qquad (1.1)$$

where P = the pressure, P_o = the peak pressure, and t = time measured from the initial peak, is of this form. The time ϕ at which $P = 0$ will be termed the initial decay-time; it is approximately equal to the positive duration at pressures below 6 lb/in.², but at higher pressures it is considerably less than the positive duration, due to the exponential character of the pressure wave. The positive duration is used as a parameter to indicate the low-frequency components of the pressure-time curve. The individual components of the apparatus which determine the response characteristics, and which are most conveniently considered separately, are: (1) the pressure-sensitive pickup, or gauge; (2) the cables and transmission apparatus; (3) amplifiers, detectors, and so forth; and (4) the recording device.

(i) Frequency response of gauge. A finite time is required for the shock wave to travel across the gauge. This time, which will be called the gauge-crossing time, depends on the diameter of the gauge and the velocity of propagation of the shock front. For the usual pressure-time curve, which decays with time, an error is introduced by the finite gauge-crossing time which causes the measured pressure to be too low [8]. The error is given by

$$\delta_1 = \frac{1}{2}\frac{\tau}{\theta} \qquad (1.2)$$

where δ_1 = the fractional error in the peak pressure, τ = gauge-crossing time in milliseconds and θ is the initial decay-time of the pressure-time curve in milliseconds.

The usual practice at this laboratory is to mount the gauge with its sensitive faces perpendicular to the shock front. This orientation, called "edge-on," is used in order to minimize the increase in pressure on the gauge by reflection of the shock wave and to decrease interference effects between the sound wave set up in the gauge and the pressure wave in the air [8]. It also serves to reduce the strength required in the gauge to resist the force exerted by the shock wave.

Since most gauges are of circular cross-section, the crossing time for a gauge used edge-on to the shock is determined by the diameter of its sensitive portion. Thus $\tau = a/U$ where a = diameter of the gauge (ft) and U = shock-front propagation velocity in ft/msec.

If a gauge is to introduce an error of no more than 1 percent in the peak pressure of a wave from a 2-lb charge at a pressure level of 75 lb/in², its maximum diameter is limited to about 1/8 in. For the measurement of the pressure wave from a 10,000-lb bomb at a pressure level of 3 lb/in², however, a gauge 10 in. in diameter is satisfactory. The corresponding initial decay times are 0.2 and 60 msec, respectively.

An additional limit to the high-frequency response of a gauge unit is imposed by its natural resonant frequency. In the case of crystal gauges (in which pressure is applied directly to the gauge without use of diaphragms) the resonant frequency is so high that in actual practice it does not constitute a limitation. In the case of diaphragm gauges (such as condenser microphones, strain gauges, and so forth,) the resonant frequency of the diaphragm does constitute a practical limitation. Elevation of the resonant frequency by increase of diaphragm rigidity results in a corresponding loss of sensitivity and in such cases it is necessary to adopt a suitable compromise between the demands of sensitivity and high-frequency response.

Certain types of gauges respond to a static change in pressure, that is, they have full sensitivity to signals whose frequency approaches indefinitely close to zero, but other types, of which the most important is the piezoelectric gauge, do not possess this advantage. The low-frequency response of a piezoelectric gauge, for example, is limited by the fact that the charge produced by the gauge leaks away through the finite resistance of the gauge circuit. The decay is exponential in character, its rate being determined by the product of the total capacity and the leakage resistance (that is, the time constant of the gauge circuit). In Ref. 25 it is shown that, due to the time constant of the gauge circuit, the measured positive impulse is lower than the true value by a fractional error not in excess of

$$\Delta_1 = \frac{2}{3}\frac{T}{\lambda_1} \qquad (1.3)$$

where $\underline{T}$ is the positive duration of the wave and λ_1 is the time constant of the gauge circuit. For example, the time constant required to introduce an error in the positive impulse of no more than 1 percent is approximately 70 msec for a wave from a 1-lb charge at 10 lb/in.^{2} pressure level and 4 sec for a wave from a 10,000-lb bomb at 3 lb/in.^{2} The corresponding positive durations are about 1 and 60 msec, respectively.

(ii) Cable response. An unterminated transmission line causes appreciable distortion in the pressure signal if the length of the line is a large fraction of the quarter-wave-length of the highest important frequency component in the frequency spectrum of the transient. This distortion can be eliminated if the line is properly terminated, but other circuit requirements at the ends of the cable may sometimes prevent exact matching of impedances. Such is the case, for example, where the use of piezoelectric gauges necessitates the maintenance of high impedance. If modulated carrier waves are used, high-frequency termination is almost always necessary, but this problem has not been investigated at UERL.

Two types of distortion are likely to occur in short as well as long cables used in the circuit of a piezoelectric gauge: one type of distortion is due to simple leakage across the cable, resulting in a lowering of the time constant of the gauge circuit. The other is due to dielectric dispersion, that is, a change of capacity with frequency, resulting in a frequency dependence of the voltage developed across the cable. Distortions which might be present in radio transmission of a modulated carrier-wave system have not been investigated at this laboratory.

(iii) Amplifier frequency response. To a satisfactory degree of approximation a multi-stage amplifier can usually be represented by an equivalent single-stage amplifier.

The sinusoidal high-frequency-response characteristics of a single-stage resistance-capacitance or direct-coupled amplifier can be expressed in terms of an equivalent exponential response to a unit-step function. The response to a transient signal which decays linearly with time is such that the peak amplitude recorded is too low by a fractional error δ_2 given by

$$\delta_2 = \beta \ln \left(1 + \frac{1}{\beta}\right) \tag{1.4}$$

where $\beta = \kappa/\phi$ and ϕ is the time in milliseconds in which the linear signal decays to zero amplitude; it is equivalent to the initial decay-time of the pressure-time curve. This equation can be obtained from equations given in Ref. 8 or 33. κ is the time constant of the exponential response of the amplifier in milliseconds and is equal to the product of the effective load resistance of the amplifier with the total capacity shunting the load resistance. The frequency in kc/sec at which the amplifier response is down approximately 3db (30 percent) from its midband value is given by

$$f_c = 1/2\pi\kappa.$$

A multistage amplifier without high-frequency compensation can also be represented by an exponential response to a good degree of approximation, and even a compensated amplifier is reasonably well represented in these terms.

In actual practice the amplifier receives a signal which has already been distorted by the gauge. The maximum amplitude recorded by the amplifier is lower than the maximum output of the gauge by a fractional error δ_3 given by [8]

$$\delta_3 = \beta \ln \left[1 + \frac{1}{\alpha}\left(1 - e^{-\alpha/\beta}\right)\right] \tag{1.5}$$

where $\alpha = \tau/\phi$, $\beta = \kappa/\phi$ and the other notation is the same as above. The actual appearance of the distorted transient is shown in Refs. 8 and 33. The total error in peak pressure due to attenuation of high frequencies in the gauge and amplifier is the sum of the two corrections, that is, $\delta_1 + \delta_3$. If δ_1 is known to be 1 percent and it is required that the amplifiers introduce an additional error δ_3 not greater than 1 percent, the amplifier must have an f_c equal to 300 kc/sec for the case of a wave from a 2-lb charge at a pressure level of 75 lb/in.², and an f_c equal to 1700 cps* for the case of a wave from a 10,000-lb bomb at a pressure level of 3 lb/in.²

Any amplifier which is not direct coupled will distort the low-frequency components of the pressure wave. An uncompensated resistance-capacitance-coupled amplifier with an over-all time constant λ_2 causes the measured positive impulse to be too low by a fractional error not in excess of [25, 33]

$$\Delta_2 = \frac{2}{3}\frac{T}{\lambda_2} \tag{1.6}$$

where T is the positive duration of the pressure wave. For an impulse measurement with piezoelectric gauges the total fractional error due to the time

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*The abbreviation cps is used for cycle/sec.

constants of the gauge circuit and the amplifier is

$$\Delta = \Delta_1 + \Delta_2 = \frac{2}{3} T \left(\frac{\lambda_1 + \lambda_2}{\lambda_1 \lambda_2} \right) \qquad (1.7)$$

where λ_1 is the time constant in the gauge circuit. This correction is not entirely accurate for compensated amplifiers.

(iv) Recording devices. The frequency response of a cathode-ray tube extends past the range of frequencies to which most other recording devices will respond, and consequently cathode-ray tubes can be used in the measurement of blast from all types of charges. Recording devices with a lower high-frequency response than cathode-ray tubes, such as string galvanometers, can be used only for the measurement of pressures from large charges.

(e) Time-base resolution. — The resolution required on the photographic record of a pressure-time curve is governed by the positive duration of the pressure signal. A resolution which will make the displacement on the film corresponding to the positive duration slightly less than the deflection on the film corresponding to the peak pressure is adequate for most purposes.

(f) Interaction of the gauge with the shock wave. — The physical presence of a gauge causes a distortion of the field of mass flow behind a shock front. This distortion results in a Bernoulli effect, subjecting the gauge to a hydrostatic pressure somewhat lower than the true hydrostatic pressure behind the shock front [23]. Since the mass velocity increases with pressure, the pressure recorded by the gauge becomes proportionately lower than the true value as the pressure level increases. Thus the gauge sensitivity will be a nonlinear function of dynamic pressure even if it is a linear function of static pressure. All pressure pickups of finite size are subject to this nonlinearity unless they are built into a properly constructed baffle [23]. Unfortunately, the importance of the air-flow effect on blast measurements has been realized only recently [6, 7, 8] and most gauges used to date were not designed to minimize error from this source.

The acceleration of a gauge by the impact of the shock wave is known to introduce a spurious signal on diaphragm type gauges [14]. The effect of acceleration on piezoelectric gauges is not known.

(g) Location of the recording equipment. — The location of pressure pickups depends on the problem being investigated; gauges have been located on the ground, a few inches to 20 or 30 ft above the ground, next to obstacles and inside buildings, ships and tanks.

The operating personnel, who are usually at the same location as the recording device, have to be at a safe distance from the explosion. For small charges, distances of a few hundred feet are safe; 1100 ft is sufficient for charges weighing up to 10,000 lb; but for very large charges, distances of many miles may be required. Cables are generally used for transmitting the gauge signal to the recording equipment, but radio transmission is required in certain applications.

In general, the system must be capable of transmitting the gauge signal over the required distance and must incorporate provisions for the protection of the transmission equipment, recording equipment, and personnel.

(h) Freedom from spurious signals. — Spurious signals can be produced in the recording equipment by the pressure wave, by other phenomena accompanying the explosion, and by the blast-measuring equipment and associated apparatus.

(i) Cable signal. Spurious signals may be produced in the cables connected to the gauge, or in the gauge itself, by the pressure wave, ground shock or fragment bow-waves.

(ii) Microphonics. Microphonic signal from vacuum tubes and associated electronic equipment can be excited in apparatus exposed to the blast, fragment bow-waves, and ground shock. Microphonics may also be caused by mechanical vibration and noise near the instruments.

(iii) Thermal signal. There are two sources of thermal signal in an explosion: the heat developed in the explosion is radiated to the gauge, and the temperature in the air behind the shock front is elevated by adiabatic compression. The type of signal produced in the gauge from these sources is a pyroelectric signal and is not to be confused with the change in sensitivity of the gauge with temperature, which is usually associated with a temperature coefficient of sensitivity. Pyroelectric signal can also be caused by changes in local air temperature or by the absorption of solar radiation by the gauge.

(iv) Transient electrical signals. A transient electrical signal may be picked up by the recording equipment from the cloud of ionized gases liberated in the detonation either by radiation or, if any of the apparatus is close enough to the explosion, by conduction. Other common transient signals which may be picked up are from the current used to initiate the detonator, from synchronizing pulses to instruments and cameras, and from sudden changes in load on the power supply. Direct fragment hits on cables or equipment before recording is completed will, of course, interfere with the records.

(v) Other electrical signals. Many different kinds of spurious electrical signals can be picked up by the equipment. These signals fall into two categories: those which are picked up when no cables or other connections are made external to the amplifier in the recording unit, and those which only become apparent when all components of the system are connected together. The first type of signal can be from any of the usual sources; 60 cps from transformers, power lines and generators, high-frequency pickup from motors and generators, pickup from oscillators, spurious oscillations such as parasitics and motor-boating, and so forth. The second category includes radio signal, 60 cps, particularly from generators and power lines in the field, and ignition noise from generators.

(i) Reliability and simplicity. — The testing of the blast from explosives, (particularly from large charges) involves considerable time and expense, and frequently the tests cannot be repeated. Consequently the blast-measuring equipment must be reliable. All the equipment has to withstand the effects of the explosions as well as frequently unfavorable operating conditions. Convenience and simplicity of operation are important, particularly for mobile and portable equipment. Semiautomatic operation is an aid in preventing human errors and in speeding up the recording of small charge measurements, in which over 30 shots per day may be measured with one set of equipment.

1.2. Comparison of electrical methods for the measurement of pressure-time curves.

All of the electrical methods of determining the pressure-time curve from an explosion in air depend on the measurement of an electrical signal due to mechanical displacement produced by the pressure wave in the elements of a pressure-sensitive pickup. The main characteristics of the recording system are governed by the nature of this pressure pickup.

A comparison will be made between piezoelectric, condenser-microphone, and resistance-strain gauges, and between the electrical recording systems used with these gauges. These are the types of gauges used to the greatest extent for the measurement of air blast in Great Britain and the United States; other electrical methods of measuring blast are mentioned briefly in Ref. 1 and Ref. 8.

(a) Piezoelectric gauges. — Certain classes of crystals, when subjected to mechanical stress, have the property of developing electrical charge on various crystal faces. Such crystals are called "piezoelectric."

Piezoelectric gauges have been used by most of the laboratories engaged in air-blast measurements, and most of the results now available were obtained with such gauges.

Piezoelectric crystals for use in the measurement of shock waves in air must be divided into two groups: those which respond to hydrostatic pressure, and those which do not. Tourmaline and lithium sulfate are in the first class; quartz, Rochelle salt, and ammonium dihydrogen phosphate (ADP) are in the second. A housing is generally placed around gauges made of substances not sensitive to hydrostatic pressure so that the application of pressure is restricted to certain of the crystal faces.

Piezoelectric gauges have been found to be linear with static pressures ranging from less than 1 atmosphere to a few hundred atmospheres.

Piezoelectric crystals are also pyroelectric, that is, a change in the temperature of the crystal produces a charge. A uniform increase in temperature, like a decrease in hydrostatic pressure, causes the crystal to expand, so that the charge developed is of opposite polarity to that developed by an increase in pressure. Piezoelectric crystals which are not hydrostatically sensitive do not yield a pyroelectric signal when subjected to a uniform temperature change. However, in practice, thermal gradients are present which give rise to a pyroelectric signal even in non-hydrostatically sensitive crystals, and the polarity of the signal depends on the particular piezoelectric moduli affected by the thermal gradients.

The temperature coefficient of the piezoelectric constant of some piezoelectric crystals, such as quartz and tourmaline, has been found to be very small (in measurements made at this laboratory) over the ordinary range of outdoor temperatures, although certain other crystals, such as Rochelle salt, have a large temperature coefficient in this region. The temperature coefficient of the piezoelectric sensitivity is not simply related to the pyroelectric coefficient.

The charge generated by a piezoelectric crystal distributes itself over the parallel capacity C of the gauge circuit, the voltage developed at the input to the amplifier being inversely proportional to the magnitude of this capacity. (See Appendix II, Ref. 8) As pointed out in Sec. 1.1(d), the presence of finite leakage resistance R introduces an effect equivalent to low-frequency distortion; hence it is necessary to maintain a value of the time constant RC of the gauge circuit high enough so as to introduce negligible error in the measurement of the positive impulse, $\int_0^T p(t)dt$.

For large values of positive duration T, which occur when measuring the blast from large charges, it is necessary to have correspondingly large values of the time constant. This can be achieved by increasing the padding capacity C (R being always maintained as high as possible). Since an increase in C produces a corresponding decrease in available signal level, it is frequently necessary to seek a suitable compromise between the demands of low-frequency response and amplifier sensitivity. The quantitative nature of these requirements also depends upon the pressure level at which measurements are to be made and on the coulomb sensitivity of the gauge. See Chap. 3 and 5.

Quartz and tourmaline are the most commonly used substances for air-blast measurements. Rochelle salt has also been used, as well as ADP. Lithium sulfate has recently been suggested, but has not been tested at the time of writing.

The cables used to connect the gauges to the amplifiers have been as long as 1500 ft but, because of the high capacity involved, this length requires high-gain amplifiers, which are necessarily sensitive to spurious electrical signals. In order to minimize the signal attenuation caused by long cables, short cables have been used in conjunction with impedance transducers (field preamplifiers) which are placed comparatively close to the gauge. The impedance transducers, however, have not been entirely satisfactory (see Sec. 5.2). The cable used must be free from cable signal in the region exposed to blast, should have very little dielectric absorption, and may have to be properly terminated to reduce high-frequency resonances.

The advantages of a piezoelectric system are: (1) the gauges are linear over wide ranges of pressure; (2) the natural resonant frequency of the gauge is high; (3) the temperature coefficients of the piezoelectric sensitivity of some piezoelectric substances, such as quartz and tourmaline, are very low; (4) certain piezoelectric crystals, namely, quartz and tourmaline, have proven to be very durable.

The disadvantages are: (1) The low-frequency response is limited by the attainable leakage resistance of the gauge and cable. (This is, in practice, a limiting factor for blast measurements on only the very largest charges.) (2) The gauges are very sensitive to thermal changes (pyroelectric effect). (3) High-gain amplifiers are frequently necessary so that the system is easily affected by extraneous signals. (4) It is sometimes difficult to maintain very high impedance in the gauge cables. (5) High-impedance cables are susceptible to pickup of signals from external sources such as radio transmitters, power lines, and so forth.

Piezoelectric gauges are, therefore, more suitable for measurements on small charges than on very large charges.

(b) Condenser-microphone gauges. — Condenser-microphone gauges for use in blast measurements usually consist of two metal diaphragms which serve as plates of a condenser and which can be strained by an external force, thus changing the capacity of the gauge. Stiff diaphragms must be used in order to obtain a sufficiently high natural resonant frequency. This results in a sensitivity (that is, change in capacity with pressure) which, for the measurement of blast from small charges, is much smaller than for the measurement of the pressures from large charges. The sensitivity of a condenser-microphone gauge used with a frequency-modulated system, however, is probably considerably greater for the measurement of blast from large charges than is the sensitivity of a piezoelectric system. The range of pressures to which a single diaphragm responds linearly is limited, and consequently different diaphragms have to be used to cover the entire range of pressures that is of interest.

A number of schemes for using condenser-microphone gauges to measure pressures in internal combustion engines have been developed, and some use has been made of condenser gauges for measuring pressures in gun barrels. In most of these systems the variation in capacity is used to modulate the amplitude of a radio-frequency carrier wave [9, 10, 11]. In some of these systems, particularly the one developed at General Motors [10, 11], cable noise is reduced by cable-matching networks at the gauge and the recording equipment.

Two techniques for measuring air blast with condenser-microphone gauges have been developed in which the capacity variation is used to generate a frequency-modulated carrier wave. The system developed at the Ballistic Research Laboratory [12] uses a very short connection between the gauge and the modulated oscillator, while the system developed at Princeton University [13] is made to adapt cables up to 1000 ft between the gauge and oscillator. Frequency-modulated systems are undoubtedly preferable to amplitude-modulated systems because they are less susceptible to spurious signals. Although high-gain amplifiers are required, most of the gain is in tuned radio-frequency or intermediate-frequency stages; and the wide-band gain required, which depends on the linear range of the discriminators (frequency detectors), is relatively low. Since the gain necessary in direct-coupled amplifiers between the discriminator and the recording device is not very high, a direct-coupled amplifier is easily constructed so that the over-all system can be made sensitive to static pressure. For experimental problems in which radio transmission is required, because the gauge cannot be connected directly to the recording equipment, frequency-modulation techniques are probably the most satisfactory.

A unique method of measuring positive impulse with a frequency-modulated system was developed at the Ballistic Research Laboratory. The frequency-modulated carrier is heterodyned to an intermediate frequency in the audio range, and this is impressed on a neon tube. The dots produced on the neon tube are modulated by the pressure signal, and the number of dots in the positive phase of the pressure-time curve in excess of the number of dots from the unmodulated intermediate frequency is the excess pressure in the wave. If the frequency of the unmodulated carrier is known or calibrated, the positive impulse can be obtained by counting dots on a photograph of the neon bulb. This technique has been used for the measurement of the pressure wave from large charges where low-frequency dots give sufficient resolution, but it may not be practical when used to measure the blast from small charges.

The advantages of a frequency-modulated condenser-microphone system are: (1) The gauge is sensitive to static as well as dynamic pressure, and the system is sufficiently sensitive to use with direct-coupled amplifiers. (2) It is not particularly sensitive to temperature changes and for most applications can probably be made entirely free from pyroelectric signal. (3) This system should be relatively insensitive to spurious signals. (4) Recording equipment of this type, being frequency-modulated, is more practical for radio transmission than is either an amplitude-modulated system or a system which does not inherently involve a modulated-carrier wave. (5) A rapid method of obtaining the positive impulse from the records is practical for large charge measurements. The disadvantage is: (1) A diaphragm gauge has a lower natural resonant frequency of oscillation than a crystal gauge. (Gauges of sufficient sensitivity have been made with a resonant frequency of about 100 kc/sec [13]).

The condenser-microphone gauge may well prove to be the most practical type of gauge, but at present it has not been used very extensively and may contain inherent difficulties which have not yet been realized. It must be kept in mind that the precision and band width of ordinary FM circuits are not designed to meet the standards required for accurate blast measurements.

(c) Resistance-strain gauges. — A gauge developed at the David W. Taylor Model Basin [14] makes use of the fact that the stretching of a wire produces a change in its electrical resistance. In these gauges a spiral layer of fine Advance wire is cemented to the back of a diaphragm which is deformed by the blast. The resistance element is used as part of a voltage divider so that changes in resistance are converted into voltage fluctuations which can be transmitted to the amplifiers over low-impedance lines.

The resonant frequency of the diaphragm in the TMB gauge is of the order of 30 kc/sec, which is considerably lower than the resonant frequency of the condenser-microphone gauges developed at Princeton. An electronic filter is used at Taylor Model Basin to remove the resonant oscillations of the gauge from the output of the amplifier. For general use the TMB gauge is less sensitive than piezoelectric gauges.

Strain-type gauges respond to static pressures but the thermal sensitivity of resistance wires is comparable to their pressure sensitivity, so that thermal signal limits the usable low-frequency response. The TMB gauge was developed primarily for the measurement of gun blast, and apparently the thermal sensitivity has not been troublesome for that type of measurement. It may be possible to compensate for the thermal sensitivity of these gauges by balancing the resistance element in the gauge with an identical element, not exposed to the blast, in a bridge network. Strain gauges, made by the Baldwin-Southwark Division of the Baldwin Locomotive Corporation for the measurement of static strain, use this type of temperature compensation.

The TMB gauges are of the single diaphragm type, and precautions have had to be taken to eliminate acceleration effects [14].

The advantages of a resistance-strain gauge are: (1) It is sensitive to static pressure. (2) The effect of blast on the gauge cable is relatively small. The disadvantages are: (1) The gauge is insensitive, and consequently direct-coupled amplifiers of sufficient gain are difficult to construct, so that use cannot be made of the static sensitivity. (2) Because of the high gain, the system is sensitive to spurious signals. (3) The gauges are sensitive to thermal signals. (4) The natural resonant frequency of gauges which have been constructed is low. (5) Acceleration effects are more troublesome than with other types of gauges.

Chapter 2

OUTLINE OF AIR-BLAST EQUIPMENT USED AT UERL

The equipment in use at UERL for the measurement of air blast employs tourmaline piezoelectric gauges, and the electronic equipment has been designed primarily to record the transient signal generated by a piezoelectric gauge exposed to a shock wave from a high explosive in air. Other electronic equipment has been designed at UERL for the measurement of underwater shock waves [33].

The tourmaline gauges usually consist of from four to eight circular discs 7/8 to 1-5/8 in. in diameter and have a sensitivity ranging from 20 to 100 $\mu\mu$coulomb/(lb/in.^{2})

The gauge is connected to an amplifier by coaxial shielded cables from 50 to 1500 ft in length which have capacities ranging from 20 to 40 $\mu\mu$f/ft. These cables are selected to have very little noise (cable signal) and dielectric absorption, and when long cables are used they are provided with terminations to reduce high-frequency distortion. In some cases, field preamplifiers are employed to reduce the capacitative attenuation of the gauge signal which is introduced by a long cable. When field preamplifiers are used a low-impedance coaxial line is connected between the preamplifier and the amplifier at the recording station.

The amplifiers have a maximum usable gain of 96 db (60,000), a high input resistance, and a high-frequency response down 3 db (30 percent) at from 70 to 100 kc/sec. The best response to a unit step is flat for a maximum of 60 msec. The gain of the amplifiers is adjustable. Two types of amplifiers are employed: push-pull amplifiers designed specially for air-blast measurements, which are included in a mobile laboratory; and modified commercial oscillographs, which are used with preamplifiers.

The signal from the amplifiers is applied to cathode-ray tubes, and oscillograms are photographed on fixed- or moving-film cameras. The time base is provided either by the moving-film camera or, when fixed-film cameras are used, by electronic single-sweep generators. The oscillograph trace is brightened by an electronic beam-brightener synchronized with the explosion by blast-operated switches or by a sequence device connected into the electrical circuit which initiates the detonation. When sweep-generators are employed, they are synchronized with the pressure wave in the same manner.

The gauges are calibrated under static and dynamic conditions and hold their calibrations for fairly long periods of time. The over-all amplitude sensitivity, excluding the gauge sensitivity, is calibrated with a unit step of voltage of known amplitude immediately before and after each recording, and the time base is calibrated during the recording or immediately preceding it.

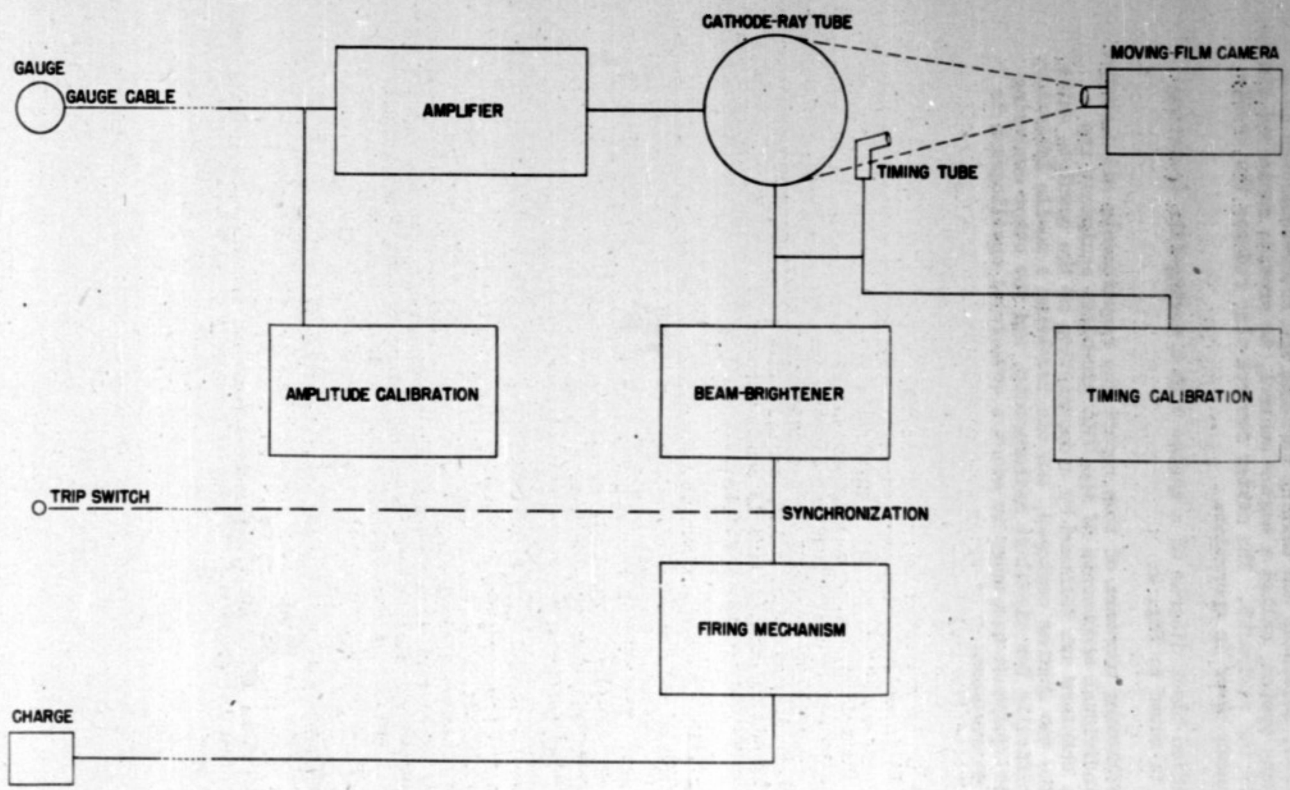

FIG. 2. BLOCK DIAGRAM OF EQUIPMENT FOR MEASUREMENT OF AIR BLAST.

Calibration, switching and testing circuits are inter-connected in a master switching system, called a master control, to provide rapid and simple functioning of the equipment. The master control also reduces the possibilities of human error in operation.

A simplified block diagram of a system with a moving-film (rotating-drum) camera is shown in Fig. 2.

In the following chapters of this report the requirements and description of the individual components of the UERL air-blast equipment are given. These chapters are followed by a description of the complete units involved in the two systems employed, the one involving a mobile laboratory designed specifically for air-blast measurements, and the other employing the electronic equipment necessary to adapt a commercial oscillograph to this type of measurement.

Chapter 3

PIEZOELECTRIC AIR-BLAST GAUGES

Piezoelectric gauges have been used exclusively at this laboratory for air-blast measurements. The general requirements of gauges for blast measurements and a comparison of different systems of blast measurement have been discussed in Chap. 1, where it was pointed out that piezoelectric gauges are not necessarily the best type of gauge for this purpose. This chapter will be devoted to more detailed discussion of piezoelectric gauges, with particular reference to the construction and characteristics of the tourmaline gauges used at UERL. The material in this chapter is more thoroughly treated in Ref. 8.

3.1. Comparison of piezoelectric substances

(a) General considerations. -- There are two classifications of piezoelectric crystals which are important in the use of such crystals for blast measurements:

(1) In crystals of Rochelle salt and ADP (ammonium dihydrogen phosphate) all of the polarization is produced by a shearing stress with respect to the principal axes of the crystal, while in quartz, tourmaline, and lithium sulfate the polarization is primarily due to a stress normal to certain of the principal axes. The shear-sensitive crystals are more sensitive than the latter type, but have inferior electrical and mechanical characteristics.

(2) It is necessary to distinguish between those crystals such as quartz, Rochelle salt, and ADP, on which the application of a hydrostatic pressure to all the faces of the crystal does not produce a net charge, and those crystals such as tourmaline and lithium sulfate which do have a net charge under these conditions. Gauges containing a crystal which is not hydrostatically sensitive must be provided with a means of preventing the shock pressure from exerting a force on certain of the crystal faces.

Uniform heating of a crystal produces the same charge as a decrease in hydrostatic pressure, so that crystals which are not hydrostatically sensitive will not give rise to a pyroelectric signal from a uniform temperature change. They will, of course, respond to non-uniform temperature changes.

The piezoelectric substances used most extensively for air-blast gauges have been quartz and tourmaline. The more important properties of these crystals, as well as those of a few other substances not so widely used, are compared in the following:

(b) Quartz gauges. -- Quartz is generally considered to be one of the best materials for piezoelectric blast gauges. Although it has relatively low sensitivity compared to Rochelle salt and ADP, the temperature coefficient of its piezoelectric constant is small, it is mechanically strong and it has a very high leakage resistance. It must be mounted in a housing because it is not hydrostatically sensitive, but at the same time it is not as sensitive to pyroelectric signals as is tourmaline. Quartz gauges have been used by the Road Research Laboratory and the Armament Research Department of Great Britain, by the Princeton University Station of Division 2, NDRC, [16] and by the Ballistic Research Laboratory at Aberdeen Proving Ground.

(c) Tourmaline gauges. — The electrical and mechanical characteristics of tourmaline are almost identical to those of quartz except that tourmaline is hydrostatically sensitive and does not require a housing. Since, in order to reduce the effects of air flow, it is necessary to surround an air-blast pressure gauge with a baffle, the fact that tourmaline is hydrostatically sensitive and, therefore, does not require a housing is not as great an advantage in air-blast gauges as it is in gauges for the measurement of underwater shock waves. Tourmaline gauges appear to be more sensitive to pyroelectric signals than British-type quartz gauges. Tourmaline has been used extensively for underwater shock-wave studies both at the David W. Taylor Model Basin and at UERL, and it has been employed almost exclusively for air-blast measurements at UERL and the Stanolind Oil and Gas Company. More recently it has been used at the Ballistic Research Laboratory and at Princeton University.

(d) Rochelle salt gauges. — Rochelle salt is about 100 times more sensitive than tourmaline and quartz. It is not hydrostatically sensitive and has a Curie point in the neighborhood of room temperature so that the piezoelectric constant has a marked temperature dependence. The dependence of the sensitivity of a Rochelle salt gauge on temperature is due primarily to a change in the equivalent capacity of the crystal, so that if no current is drawn from a Rochelle salt gauge the emf produced is relatively independent of temperature.

Two methods for using Rochelle salt blast gauges have been proposed in which the blast measurements would not be affected by the sensitivity of the gauge to temperature: one technique is capable of determining the positive impulse in the pressure wave but does not give a measurement of the peak pressure. In this method the pressure in the blast wave at the point where the Rochelle salt gauge is located is determined by an independent measurement, such as by measurement of the velocity of propagation of the shock wave [17], and is used to calibrate the sensitivity of the gauge at the instant the recording is made.

The second technique involves the use of a low-capacity very high-impedance gauge circuit which draws negligible current from the crystal. This method is limited by the values of leakage resistance that can be maintained in the gauge circuit, and it also requires a non-microphonic preamplifier. At temperatures over 90° F it has been found that the impedance of Rochelle salt gauges made by the Brush Development Company drops to a value as low as 4 megohms, hence the second method is not practical in warm weather.

Rochelle salt has also been found to introduce a distortion which is equivalent to a rising response to a unit step [8]. Its mechanical characteristics are also poor, and consequently Rochelle salt is not well adapted to quantitative amplitude measurements, although it is useful for producing signals for timing or synchronization purposes.

(e) ADP gauges. -- Ammonium dihydrogen phosphate (ADP) is similar to Rochelle salt except that its sensitivity is lower, its temperature dependence is not as marked and its leakage resistance is somewhat higher than the latter, although not comparable to that of quartz and tourmaline. It was at one time used at the Ballistic Research Laboratory.

(f) Lithium sulfate gauges. -- Lithium sulfate has been introduced only recently, and very little information on the characteristics of gauges made from this substance is available.

3.2. Construction of tourmaline gauges

The tourmaline gauges in use at UERL are an outgrowth of gauges originally developed at Harvard University in the fall of 1942 [18]. The design of these gauges was based on previous experience with gauges for underwater use. The construction and further development of tourmaline gauges was continued by the Stanolind Oil and Gas Company [19, 20, 21], and more recently by the Reeves Sound Laboratories and the Cambridge Thermionic Corporation [22]. Only a brief description of the gauges will be given here; more detailed information will be found in Ref. 8 and Refs. 19 to 22, inclusive.

(a) General characteristics. -- The sensitivity of a tourmaline gauge is proportional to the area of the crystal; thus large crystals are necessary to obtain high sensitivity. The size of the crystals used in a gauge has usually been restricted, by the mechanical characteristics and size of the available tourmaline, to a diameter of about 1-5/8 in. A single disk of this size has a sensitivity approximately equal to 24 $\mu\mu$coulomb/(lb/in^2), but most gauges used at UERL consist of four disks, forming a four-pile gauge, with a maximum sensitivity of about 95 $\mu\mu$coulomb/(lb/in^2).

The maximum diameter is also limited by the gauge crossing time [see Sec. 1.1(d)], and for the measurement of blast from very small charges, a gauge diameter as small as 1/8 in. is necessary. The smallest standard air-blast gauge at UERL, however, has been 7/8 in. in diameter.

The problem of reducing the nonlinearity introduced by the air-flow effect is being investigated at the time of writing. Theoretical investigations, [23, 24] as well as some experimental information [8], indicate that the ratio of the thickness to the diameter of the gauge, which is known as the aspect, should be small and that the sensitive part of the gauge should be in the center of a baffle.

The pyroelectric signal produced in a gauge by the increase in the temperature of the air behind the shock wave and by the thermal radiation from the explosion is reduced in UERL gauges by coating the gauge with a thermal insulating material. This insulation delays the flow of heat to the gauge elements until the recording has been completed. About 1/8 in. of insulation is sufficient to prevent spurious signals from interfering with measurements on all but the largest high-explosive charges, but explosions of very long duration, such as those encountered in measurements of blast in enclosed spaces, require greater insulation. Details of the calculation of the heat flow through the insulation are given in Ref. 25 and the experimental problems encountered are described in Ref. 8. Gauges should be covered with a light-colored coating to reduce the absorption of radiation. Although this thermal insulation is effective in eliminating pyroelectric signal caused by temperature changes from most explosions, local temperature changes in the air or variations in the intensity of solar radiation striking the gauge may, if the equipment has a long over-all time constant, cause drift of the oscillograph spot. These effects are particularly noticeable on partly cloudy days when the sunlight striking the gauge is of variable intensity, when it is very windy, and when it is snowing. At times pyroelectric signals of this type have been so large that the oscillograph trace has been deflected off the screen of the cathode-ray tube, causing the loss of the blast record, and this kind of signal limits the usable low-frequency response of the recording system. British-type quartz gauges show a much smaller response to pyroelectric drift than UERL tourmaline gauges.

The electrical signals which occur simultaneously with an explosion are picked up by an unshielded gauge and cause a displacement of the oscillograph trace before or during the time the blast wave strikes the gauge. An electric shield completely surrounding the gauge elements and attached to the cable shield by a secure low-resistance connection eliminates this signal entirely.

The mechanical strength necessary in a gauge depends on the pressures to which it is subjected, and the tourmaline gauges have had to be reinforced with a metal tab for use at pressures above 10 to 15 lb/in^2.

The cables to which the gauges are attached are of special types which are selected to have a minimum amount of cable signal. These types are described in Chap. 4. A spurious signal similar to cable signal can arise in the gauge if there is insulation present between the gauge shield and the signal electrodes, so that gauges are assembled in an arrangement which minimizes the area of the sensitive elements in contact with insulation.

(b) Description of specific gauge types. — The gauges in use at present are manufactured by the Cambridge Thermionic Corporation and consist of four tourmaline disks built around a central steel tab. The tourmaline disks are made up with a standard thickness of about 0.04 in., although disks as thin as 0.025 in. have been used, and with diameters of 7/8, 1-1/8, and 1-5/8 in. Electrodes are applied to the faces of these disks by coating with a silver paint and baking. Two of these disks, with a thin foil of solder between adjacent faces, are placed on either side of the steel tab, which is 1/16 in. thick, and the whole assembly clamped and sweated together in an oven. Thin fans of wire, inserted between each pair of disks before sweating, are soldered together and to the live leads of the cable. After the edges of the disks have been insulated with latex, the steel tab and the outside faces of the disks are connected together and to the cable shield by applying a layer of conducting paint, which serves as an electrostatic shield. A strong and rigid structure is obtained by fitting the steel tab of the gauge into a brass tube fastened to the cable, which is usually a lead-sheathed cable about 18 in. long. The gauge is coated with wax or a rubber-like compound to provide thermal insulation and weatherproofing.

Gauges were originally built without a metal center tab, but they could not be employed reliably for the measurement of pressures above 10 to 15 lb/in^2 because the neck of this type of gauge was too weak. The present gauges have been used successfully up to 150 lb/in^2, which is the highest pressure to which they have been exposed. These steel-tab gauges have not been used "face-on" to the blast but it was found that brass-tab gauges bend when used "face-on" at pressure of 200 to 300 lb/in^2

Recently baffled gauges have been designed for the purpose of reducing the effect of air flow. They consist of four 7/8-in. diameter disks surrounded by an annular brass ring with an outside diameter of 2.7 in. and a thickness of 0.35 in. It is hoped that these gauges will show less non-linearity to dynamic pressure than the older type gauges, but they have not yet been exhaustively investigated [8]. Gauges which can be flush-mounted in a baffle of any size or in the ground have also been designed but have not yet been tested [8].

The gauges which have been described are intended primarily for use with unbalanced gauge cables but other types of gauges have been designed especially for use with balanced lines. The advantages of a balanced system are described in Sec. 4.1(a). Two types of push-pull gauge arrangements have been developed: Type 1 contains one or more crystals connected in parallel to the two live leads of the cable and without any connection to ground; the output voltage from a gauge of this sort is approximately proportional to twice the charge developed by the gauge divided by the almost equal capacity of each lead of the cable ground (see Chap. 9).

Type 2 push-pull gauge arrangement can be made from two ordinary gauges intended for use with an unbalanced line: A positive gauge, which is one which gives a positive signal when subjected to an increase in pressure, is connected between one lead of the cable and ground, and a negative gauge is connected between the other lead of the cable and ground. The output voltage of gauges of equal sensitivity connected in this arrangement is approximately equal to the charge developed by the gauge divided by the almost equal capacity of each lead of the cable to ground. Thus the sensitivity of each of the gauges used in this circuit must be equal to the sensitivity of a single push-pull gauge of Type 1 if the same output signal is to be obtained from both arrangements.

Type 2 push-pull gauge arrangements containing two ordinary single-ended gauges of opposite polarity, as well as Type 1 push-pull gauges, have been used at this laboratory. The Type 1 push-pull gauges which have been made in the past have not been very satisfactory because of their poor construction. They are subject to a signal similar to cable signal from the insulation required between the live electrodes and the gauge shield; and although the use of glass disks as an insulating material eliminates this cable signal, the disks increase the aspect of the gauge and consequently accentuate the effect of air flow.

The metal central-tab design is particularly well adapted to the construction of integral Type 2 gauge units in which the pairs of crystals mounted on either side of the central tab have opposite polarity. Gauges of this type have not yet been tested at this laboratory.

Dummy gauges are employed to test for spurious signal in the gauges and gauge cables. Dummies are identical in construction to their prototype gauges except that they contain plated glass disks instead of tourmaline disks.

The results of blast measurements made at UERL with tourmaline gauges are described in Chap. 14.

Chapter 4

CHARACTERISTICS OF CABLES

The cables used in the gauge circuit of piezoelectric blast-measuring equipment must fulfill conditions which are peculiar to this particular application. The first part of this chapter deals with the requirements imposed on these cables and with the properties of cables which have been used at UERL. The second part of the chapter is concerned with the cables employed in other circuits of the blast-measuring equipment, and the third part with the high-frequency transfer characteristics of cables used in transmitting the gauge signal.

Cables for use with piezoelectric gauges in equipment employed for the study of underwater shock waves are described in Ref. 26. The discussion of the dielectric properties and high-frequency termination of cables, which is presented in detail in this reference, applies also to cables for use in the measurement of air blast with piezoelectric gauges.

4.1. Gauge cables

(a) Requirements of gauge cables. — (i) Capacity. In order to reduce signal attenuation to a minimum the capacity in the gauge circuit should be low. The capacity, C, of a coaxial cable, in $\mu\mu f/ft$, is

$$C = \frac{7.354\ k}{\log_{10}\left(\frac{b}{a}\right)} \qquad (4.1)$$

where a is the diameter of the central conductor, b the diameter of the shield, and k the dielectric constant of the insulation. Thus a cable with a small central conductor, a large shield diameter, and a small dielectric constant is desirable. Ordinarily cables with capacities of 20 to 40 $\mu\mu f/ft$ have been used, although specially designed cables could probably be made with a smaller capacity without an excessive increase in size.

(ii) Cable signal. A potential difference is developed between the conductors of most cables with high-resistance termination when they are subjected to a pressure wave and when they are bent or kinked, a phenomena which is called cable signal or cable noise. To some extent cable signal seems to depend on the length of line exposed to the blast and the magnitude of the pressure and impulse in the shock wave. It is believed that this effect is caused by an electrostatic charge developed by friction between the conductors and insulation of the cable and is not due to a change in its capacity. The most convincing evidence concerning the nature of cable signal is provided by the great reduction in the signal from cables with polyethylene dielectric when the surfaces between the insulation and conductors of the cable are coated with graphite. This is discussed in detail in the following.

Cable signal is investigated by exposing a cable to the blast without attaching a gauge. Usually the cable is laid out so that is lies along a radius from an explosive charge, which corresponds to the layout used for recording a pressure-time curve, but on some tests it is stretched out in a straight line and the charge placed along the perpendicular bisector to the cable. To test the possibility that a spurious signal of this sort may arise either in gauges or in connectors, a dummy gauge or an unattached plug is connected to the end of the cable and exposed to the blast. The signal from the cable is recorded in the usual manner for recording blast waves except that the amplifiers are operated at maximum sensitivity.

The results of tests of this type are extremely difficult to analyze because they are not reproducible. In general, the signal produced by a cable laid out along a radius from the charge gradually increases in magnitude to a positive or negative maximum a short time after the cable is struck by the blast and then may either increase, decrease, or remain at about the same level, for some time. Frequently there are no sharp discontinuities in the slope of the record, but there are many exceptions, and discontinuities may occur if the cable is laid out with sharp bends. From shot to shot a given cable does not necessarily produce the same type of record, or even give rise to a signal of the same polarity, and in some cables the signal decreases with increased exposure to the blast. If the cable is not used for a week or so it seems to resume its original condition and the signal becomes as large as it was before being subjected to the pressure wave. The signal from cables which are relatively insensitive to blast pressures is usually more reproducible than the signal from the more sensitive cables. The signal from a dummy gauge or a plug is usually of short duration.

In recording a pressure wave, the cable is led back directly from the gauge so that cable signal, except that arising in the gauge itself, does not affect the peak pressure. Cable signal constitutes a serious problem because, by virtue of the long duration of the spurious signal, the measurements of positive impulse and positive duration may be appreciably distorted. For example, suppose that the cable signal can be roughly represented by a signal of constant amplitude (that is, a step wave) equal to 5 percent of the peak pressure recorded by the gauge: the apparent impulse due to cable signal would then be 10 percent of the true positive impulse in a linearly decaying pressure-time curve. If the pressure-time curve of the blast wave were of exponential shape, and if it were integrated to four times its time constant, the apparent impulse due to cable signal would be 20 percent of the true impulse in the wave. The actual error in the impulse may be either negative or positive, and is usually not consistent from one shot to the next.

In addition to being a direct effect of blast, cable signal has other causes. The bow-waves of fragments from cased charges produce hash of audio frequencies on the more sensitive cables, and slight winds have caused a slowly varying signal from sensitive cables lying on tall grass. In one series of measurements seismic waves through the ground gave rise to a signal in cables lying on the ground.

Cable signal can be reduced by: (1) using sensitive gauges so that the cable signal becomes a negligible fraction of the gauge signal; (2) developing, if possible, cables which are free from signal; (3) protecting the cables from the direct action of the blast; and (4) using "balanced" cables. In practice, the gauge sensitivity cannot be made large enough to overcome the effect of cable signal because both the diameter and thickness of the gauges are restricted by conditions described in the previous chapter. The second and third alternatives have proven to be the most practical.

A number of different types of cable have been tested for sensitivity to blast at this laboratory. The cable which gives rise to the smallest signal is British Telconax, and that giving rise to the greatest are cables with polyethylene (polythene) dielectric. Cables with Amphenol Copolene B dielectric, which is a copolymer resin of butene, may have shown a greater amount of cable signal than cables with polyethylene dielectric, but the usual cables with either of these dielectrics produce signals so large that an exact comparison is not of much practical importance. Cables with beaded polystyrene insulators have also shown very high sensitivity to blast.

When protected from the direct action of the pressure wave by threading through thin-walled electrical metallic tubing (EMT), water pipe, rigid electrical conduit, or flexible electrical metallic tubing (Greenfield), cables have shown a definite decrease in their sensitivity to blast, and protection of this type is also effective in reducing cable signal from fragment bow-waves. The pipe, or tubing, is frequently buried in the ground as additional protection. Although simple gauge mounts adapted to EMT or conduit are used at UERL (see Chap. 13), laying the cables and transporting the tubing for protection of long lengths of cable is inconvenient.

If a spurious signal, such as one due to the blast sensitivity of a cable, is of the same polarity in two lines, or in the two sides of a balanced line, it should be possible to eliminate the signal by using push-pull cables. The following balanced systems have been used in an attempt to reduce cable signal: (1) one push-pull gauge; (2) two single-ended gauges of opposite polarity; (3) one single-ended gauge and a twin cable, one conductor of which is left floating but shielded. The only balanced cables tested were rubber-microphone cables, but pairs of single-conductor cables of other types have been employed. It was found in some cases, that a balanced cable reduces the cable signal from direct blast by as much as a factor of two, but that in general cable signal is not sufficiently reproducible to be balanced out completely in this manner. Balanced lines are effective, however, in reducing the signal from a cable all parts of which are simultaneously exposed to the pressure wave, as, for example, in experiments for measuring the blast in enclosed spaces. Balanced lines are also used to reduce the pickup of electrical signals.

It is considered good practice, unless the cables, plugs, and gauges being used have been found to give completely negligible signal at the highest pressures and impulses to which they are to be exposed during the measurement of blast, to check the cable signal whenever conditions are changed and, in particular, when high pressures and impulses are to be recorded.

(iii) Leakage resistance. The leakage resistance of a cable is usually required to be 1000 megohms or greater, although it is not always possible to maintain so high a value. Polyethylene was found to have the best leakage characteristics, and rubber and Telconax the worst; but most dielectrics are perfectly adequate when dry. Cables with jackets which crack easily and allow moisture to reach the dielectric are very troublesome, particularly those which have a cotton or other absorbent wrapping. The wrapping absorbs moisture, and dampness spreads along the length of the cable, sometimes causing it to rot and usually corroding the shield. In good quality cables (shorter than 1500 ft) the leakage resistance attainable seems to be independent of the cable length. This is an empirical observation and only resistances below 1000 megohms have been considered.

(iv) Dielectric properties. The capacity of most insulating materials is found to vary with frequency, a phenomenon known as dielectric dispersion. There is also present an equivalent AC resistance (not to be confused with the static, or DC, resistance measurable with an ohmmeter) which is termed the dielectric loss or dielectric absorption. The two terms, however, are usually used interchangeably. The attenuation factor which describes the behavior of dielectrics in transmission lines at high frequencies may not be an indication of the behavior at the frequencies of importance for blast measurements. Dielectric dispersion and absorption affect piezoelectric measurements by causing the sensitivity of the gauge circuit to depend on frequency, which, in terms of transient representation, is equivalent to a dependence of the sensitivity on the time after a transient signal has been applied. Correct values of the peak pressure can be obtained by measuring the sensitivity with a charge-calibration step [see Sec. 9.2(c)] at the time corresponding to the rise time of the pressure signal. The correct determination of positive impulse, however, is not as straightforward.

In terms of frequency, in the range of frequencies of interest, the capacity of a dielectric is found to increase as the frequency decreases. If a charge-calibration step is applied to a cable, the output voltage falls quite rapidly at first and then appears to decay gradually at a much reduced rate. Typical measurements show the capacity of two-conductor rubber-microphone cable, such as Birnbach 1772, to change 30 percent from 50 to 50,000 cps, while polyethylene (Army-Navy RG-11/U) changes about 1 percent over the same frequency range. The dispersion of rubber cable was found to increase at high temperatures and remains quite large after continued exposure to high temperatures. In general, the amount of dispersion in good quality mica is very small; in polyethylene it is somewhat greater but usually is not objectionable for blast measurements; in paper condensers it is variable and in some cases quite small; and in most types of rubber it is very large.

The effects of dielectric absorption can be reduced in a number of ways: (1) by padding the cable with a good quality condenser (mica); (2) by developing, if possible, cables without dispersion; (3) by using cable compensating networks; (4) by the application of correction factors. The first method is impractical because any additional capacity across the gauge attenuated its signal. Polyethylene cables are sufficiently free from dispersion, as are certain other kinds of cables, but, with the exception of the recently developed British cable, polyethylene cables are too sensitive to blast.

Networks for reducing the effects of dielectric dispersion have been incorporated in the high-frequency termination of cables used in the measurement of underwater shock waves [26]. No attempt has been made to compensate for dispersion in cables employed for air-blast measurement, primarily because these networks introduce capacity into the gauge circuit which causes a greater amount of signal attenuation than can ordinarily be tolerated.

By the use of the charge-calibration step it is possible to apply a correction to measurements of positive impulse and positive duration made with cables having excessive dielectric dispersion. In order to do this, however, it is necessary either to obtain an analytical expression for the decay of the calibration step with time or to determine the response graphically; both these procedures are extremely laborious, even when the distortion is not large. Approximate formulas [25, 26] have been developed for correcting the positive impulse when the extent of the dispersion is small, but they are seldom used.

(v) Shielding. Shielding is used on all gauge cables to eliminate pick-up of spurious signals and because the capacity of an unshielded cable depends on its location. The pickup of radio signal and electrical disturbances from the charge has not been eliminated by using ordinary single-braided shields, and it is believed that this pickup can be decreased with heavier shielding.

(vi) Mechanical construction. In field use cables are subjected to tension, bending, abrasion, and water immersion and are used over wide ranges of temperature. The mechanical construction should be such that the electrical properties are not changed under these varying conditions and treatments.

(vii) Convenience of handling. To facilitate handling of cables they should not be too heavy, they should be flexible and should have a minimum diameter. A smooth outer jacket allows handling without gloves.

It is convenient if the cables are easy to solder and splice. Whenever possible the cables are chosen of the proper size to fit standard connectors.

(viii) Termination. Long cables have to be terminated to reduce the distortion of high frequencies. The high-frequency characteristics of a given length of coaxial cable for use with piezoelectric gauges depend primarily on the magnitude of the dielectric constant [26], provided only that the cable is ideal and has zero losses, which is a good approximation for most cables in the lengths ordinarily used. A cable with a small dielectric constant is the most satisfactory [26], both from considerations of its high-frequency properties and also because a material with a small dielectric constant provides a small cable capacity and has dielectric properties which are superior to the dielectric properties of materials with larger dielectric constants.

(b) Characteristics of specific cables. — (i) Telconax. Telconax, manufactured by the Telegraph Construction and Maintenance Company, Ltd., Works, Greenwich, England for the British Road Research Laboratory and the Armament Research Department, consists of a coaxial cable with an over-all diameter of about 0.03 in. The dielectric, information on the composition of which has not been available at UERL, is 0.145 in. in diameter and is covered by a cotton braid. A tinned copper shield covers the cotton braid and is surrounded by cloth wrap and a jacket, which is probably of the same material as the dielectric. The capacity is about 30 to 40 $\mu\mu$f/ft but varies somewhat from one sample to another.

The cable signal from Telconax is less than that from any other cable used for air-blast measurements at UERL but, nevertheless, in order to obtain negligible cable signal when it is used at pressures above 50 lb/in.^{2} with gauges having a sensitivity of 20 $\mu\mu$coulomb/(lb/in.^{2}), it is necessary to protect the cable with pipe or tubing.

The capacity change in Telconax due to dielectric dispersion is about 7 percent for a frequency change from 50 to 50,000 cps. Although, with the exception of cables containing polyethylene and polystyrene, the dielectric dispersion of Telconax is smaller than that of most other cables, its leakage resistance is not very high in damp weather. This difficulty is at least partly due to the presence of the cotton braid, which absorbs moisture and transmits it down the length of the cable by capillary action.

Mechanically this cable is very unsatisfactory. It will not stand slight abrasion or tension, becomes so stiff that it cracks in cold weather and so soft that it loses its shape in warm weather. Occasionally the central conductor cuts through the dielectric and shorts to the shield.

The shield of Telconax has to be built up with thin wire to fit Amphenol Series 80 microphone connectors but it fits the Amphenol Type 83-168 adapters for the Amphenol Series 83 connectors (Army Signal Corps No. PL-259). The cable is very difficult to solder because the dielectric melts too easily and because the shield is frequently corroded after the cable has been used in the field.

(ii) Army-Navy RG-11/U. This is a polyethylene coaxial cable with a central conductor 0.048 in. in diameter, consisting of 7 strands of No. 26 gauge copper wire, a braided copper shield, and a vinylite outer jacket. The diameter of the dielectric is 0.285 in. and the diameter of the jacket is 0.415 in. Most of the cable used at UERL was made by the Habirshaw Cable and Wire Division of the Phelps Dodge Copper Products Corporation, but this type of cable is made by many manufacturers. The dielectric has a dielectric constant of about 2.25 and the cable capacity is 20 $\mu\mu$f/ft. The characteristic impedance is 75 ohms.

RG-11/U is extremely sensitive to shock and vibration, and it is necessary that it be used sufficiently far behind the gauge not to be struck by the shock wave until the recording of the blast has been completed. In a series of blast measurements on 500- and 2000-lb GP bombs this cable had to be protected by Greenfield flexible tubing for 400 ft in order to eliminate the hash caused by fragment bow-waves. It must be laid flat on the ground to prevent the development of cable signal by slight motion due to wind, and it is very sensitive to any sort of mechanical vibration.

The dielectric properties of polyethylene are excellent; its dispersion is quite small; and it is relatively simple to maintain its leakage resistance at a high value. The shielding of RG-11/U is rather loose and does not adhere firmly to the dielectric. The outer jacket is not adequate in preventing low resistance between the shield and wet ground. The jacket became punctured when used on underwater tests.

Mechanically, with the exception of the outer jacket, the cable is satisfactory. It is not as flexible as rubber-microphone cable, being heavier and of larger diameter.

RG-11/U fits Amphenol Series 83 connectors and is easy to solder and splice.

(iii) Graphite-covered polyethylene cables. The British have developed a cable (Telegraph Construction and Maintenance Company Telcon cable PT-46R-modified) with polyethylene (polythene) dielectric, which gives less cable signal than Telconax and which has greatly superior mechanical properties as well as the better dielectric properties of pure polyethylene. The dimensions of the cable are similar to those of RG-11/U except that the central conductor is about 0.037 in. in diameter and the jacket consists of polyethylene covered by an additional jacket of tough cloth and rubber which makes the outside diameter about 0.55 in. There is a coating of graphite between the outside of the dielectric and the shield, which is reported to reduce the cable signal 4000-fold, and there is additional graphite around the central conductor which further reduces the signal by a factor of eight. The shield of this cable is much more tightly braided around the dielectric than the shield of RG-11/U.

Two 250-ft samples of RG-11/U with an Aquadag coating between the dielectric and shield, which were manufactured by the American Phenolic Corporation, have been tested at UERL. It was found that the sensitivity of this cable to blast was much less than the sensitivity of standard RG-11/U and that it was almost as insensitive to a pressure wave as Telconax. However, in one of the samples a bad spot was found which gave considerably more cable signal than did the rest of the cable. The difference between the behavior of this cable and the reported behavior of the British cable (which has not been tested at UERL) is believed to be due to the poorer construction of the former. The graphite in the Amphenol cable does not adhere well to the dielectric, and particles of graphite can be shaken out of the end of the cable. Furthermore, the shield does not fit snugly, and the center of a piece of cable 6 in. long can easily be pulled out of the shield and jacket.

Presumably, the dielectric properties of graphited polyethylene are similar to RG-11/U, but no tests of the dielectric dispersion have been made at this laboratory.

(iv) Lead-sheathed rubber cable. A lead-sheathed rubber cable was manufactured for the Stanolind Oil and Gas Company by the American Steel and Wire Company. The central conductor consists of 19 strands of 0.0093 in. tinned copper that has a total diameter of about 0.046 in. and is covered by a glass wind and 1/32 in. of 4111-S synthetic rubber with an outside diameter of approximately 0.10 in. The rubber is surrounded by a 450/2/2 glass braid and this is covered by a 1/16-in. lead sheath with an outside diameter of 0.25 in. No insulating jacket is provided over the lead. The capacity is about 50 $\mu\mu$f/ft.

The cable signal from lead-sheathed cable is almost as small as the signal from Telconax. Lead cable has been used successfully at pressures greater than 100 lb/in^2 when inserted in protective tubing [4]. It has been used extensively for the short length of cable built into the tourmaline gauges because, despite its somewhat greater sensitivity to blast, its mechanical properties are greatly superior to those of Telconax.

The change in the capacity of this cable due to dielectric dispersion is about 7 percent for a frequency range of 50 to 50,000 cps. The variation of dispersion with temperature has not been investigated. The leakage resistance which can be maintained in lead-sheathed cables is not as high as that which can be maintained in cables with polyethylene dielectric, but it is adequate for most purposes.

At this laboratory and at the Stanolind Oil and Gas Company lead cable has been covered by rubber tubing or tape to insulate the shield from the ground. It is of interest to note that no electrical pickup from an explosion occurred when this cable was used inside Greenfield tubing buried in the ground. This may have been due to either the good shielding of the lead cable or the very low resistance between its shield and the ground, or perhaps to a combination of both these factors, but unfortunately, when pickup was obtained with other cables, different equipment and layouts were involved, and simultaneous comparison with the lead cable was not made.

This cable is quite flexible considering its construction, and, except for its excessive weight, is easy to handle. It has broken on very few occasions and then probably only after considerable flexing. It has to be built up with thin wire to fit the Amphenol Series 80 connectors but fits the Amphenol Type 83-168 adapters. It is very easy to solder and splice.

(v) Double-shielded rubber cable. A special rubber cable was manufactured for the Stanolind Oil and Gas Company by the American Steel and Wire Company. This cable, which is about the same size as ordinary microphone cable, has a glass wrap over the central conductor and over the outside of the rubber dielectric, and contains two braided copper shields. More cable signal is produced by this cable than by the lead-sheathed cable, but less than is obtained from rubber-microphone cables. It has been used successfully when protected by tubing at pressures not in excess of 15 lb/in^2. It is no longer employed because better cables are available.

(vi) Rubber-microphone cables. The rubber microphone cables made by different manufacturers vary considerably in mechanical and electrical characteristics and even the same type of cable is found to vary from one lot to the next. Cables manufactured by the Belden Manufacturing Company (Types 8400 and 8401) and by the Birnbach Radio Company (Types 1872 and 1772) have been used. The amount of cable signal is in general larger than that of any of the other cables mentioned above except RG-11/U. Of the rubber cables tested in underwater experiments Belden series 8400 have been found to be the least sensitive to shock.

The dielectric dispersion of rubber cables is prohibitively large and depends on the temperature and the past history of the cable. The capacity varies considerably with temperature.

Rubber microphone cables are now never used as field gauge cables at this laboratory although, because they are convenient to handle, short lengths are included in the gauge circuit between the control equipment and the amplifiers. A sufficiently short length of rubber cable is employed so that the change in its capacity due to dielectric absorption is a negligible fraction of the total capacity in the gauge circuit.

(vii) Copper-tube cable. The David W. Taylor Model Basin developed a cable which has proved quite satisfactory for shock-wave studies in water [26, 27]. The cable consists of 1/8-in. diameter copper tubing through which is threaded a glass-insulated wire. The space between the central conductor and the tube is filled with wax.

This cable has been tested only twice in air but in both experiments the cable signal was greater than the signal from either Telconax or lead-sheathed cables, and in one of those tests it was found to be considerably worse than lead-sheathed cable [4].

The copper-tube cable is too stiff and becomes shorted too readily for convenient use in air-blast investigations.

(viii) Army-Navy RG-41/U. This cable is used at UERL when long lines are required for the measurement of underwater shock waves. It is connected to the end of a short length of copper-tube cable which is attached to the gauge, and is not exposed to the blast wave until the recording has been completed. The principal advantage of RG-41/U is that it is sufficiently rugged mechanically to withstand the tension to which it is subjected in underwater use. RG-11/U, on the other hand, does not have a satisfactory jacket for this purpose and is so sensitive to mechanical vibration that a signal is produced by the rolling of the ship from which the measurements are made.

A compensating network is employed with this cable to reduce the effects of dielectric dispersion because the dispersion is somewhat greater than is desirable. The capacity introduced into the gauge circuit by this compensating network causes too much attenuation to be practical for the use of this cable in air-blast equipment, and consequently RG-41/U has been employed for underwater measurements only.

(ix) Conclusions. The most satisfactory cable for use in air-blast measurements with piezoelectric gauges is probably the recently developed British cable containing polyethylene with a coating of graphite between the dielectric and the conductors. It is important that this cable have a sturdier and a more tightly woven shield than RG-11/U. It might be an advantage for a new cable to be provided with a double shield.

4.2. Miscellaneous cables used with blast-measuring equipment

In addition to the cables used in the gauge circuit, cables are employed for a number of other purposes. They are used for transmitting: (1) synchronization pulses; (2) switching currents; (3) signals from gauges used for timing purposes (velocity gauges); (4) the output of field preamplifiers; (5) speech over intercommunication systems; (6) currents for detonating the explosive; (7) low-current power for control circuits and electronic plate supply; and (8) high current power.

Shielded rubber microphone cable, either single- or multi-conductor, is used for transmitting signals of types (1), (3), and (5). Birnbach Types 1872 and 1772 are usually used, but most cables available on the market are satisfactory.

RG-11/U has been used for connecting the output of field preamplifiers to the amplifiers at the control point. Cables for this purpose should have a high characteristic impedance and low series resistance, and the cable shield should be insulated from the ground.

Two-conductor unshielded rubber-covered wire with No. 16 or 18 gauge conductors is employed for transmitting signals of types (2), (6) and (7). Cables such as Simplex SJ Tirex or General Electric CordX or CordX, Jr. are used. One of the safety regulations at UERL specifies that the firing line be distinctive from all other cables on the shooting site, and since SJ cables are not distinctive, they must be clearly identified in some way. A preferable type of firing line is the General Electric all-rubber shot firing cord which is made with red rubber, but it was not available during the war.

General Electric Tellurium portable power cable, flat, No. SI-58073, with two No. 6 or No. 8 conductors is used in lengths up to 50 ft for connecting 5-kw, 115-volt generators to the recording equipment. This is a very satisfactory cable because it has good insulation and is quite flexible.

4.3. Termination of cables

If a transmission line is comparable in length to a quarter wave length of the highest signal frequency to be transmitted over the line, the ratio of the output voltage of the line to the input voltage will, in general, depend on frequency. The transmission over an ideal line with zero losses may be made independent of frequency by proper selection of the terminations at the ends of the line, but this is not always feasible because of other circuit considerations. In any real line, furthermore, the velocity of propagation of the signal is affected by frequency to a small extent and there is always a certain amount of attenuation which depends slightly on frequency. Termination is necessary in two different kinds of long lines which are used in piezoelectric blast measurements: (1) cables used in the gauge circuit for connecting the gauge to the amplifier, and (2) lines used to connect the output of field preamplifiers to the amplifiers at the control point.

(a) Termination of gauge cables. — A piezoelectric gauge is a high-impedance device and, since termination of a cable for all frequencies requires terminal impedances equal to the characteristic impedance of the cable, exact matching of cables used with these gauges cannot be attained. Satisfactory response is obtained quite simply up to the neighborhood of the first resonant frequency by methods developed by Cole [26, 28, 29] and Lampson [30]. Since these reports are quite complete the detailed analysis will not be given here. Lampson's circuit is shown in Fig. 3.

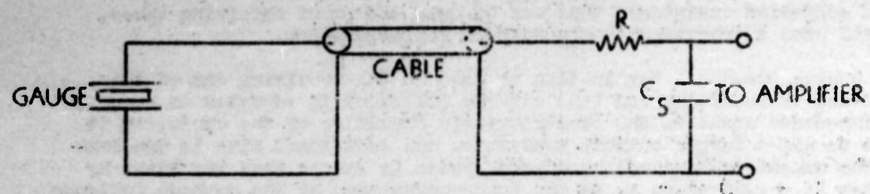

FIG. 3. CABLE-TERMINATION NETWORK (LAMPSON).

The condenser C_s is used as a standard condenser [see Sec. 9.2(c)]. For termination of 1000 ft of Telconax cable at UERL, values of R equal to about 95 ohms and values of C_s equal to 0.04 $\mu\mu f$ were employed. The response of the cable with this termination was flat within 1 percent to 100 kc/sec and had a resonance of 15 percent at about 260 kc/sec. A circuit similar to this, except that a small inductance was placed in series with R, was used with 1000 ft of RG-11/U and 100 ft of lead-sheathed cable. The values used were: L = approximately 300 turns of No. 34 enameled copper wire on a $\frac{1}{2}$-in. diameter polystyrene rod; R = 225 ohms; and C_s = 0.02 μf. The response was flat within 1 percent to 50 kc/sec and, although a resonance of less than 50 percent occurred at about 260 kc/sec, it was not passed by the amplifiers.

Ordinarily long cables are required only for measurements of the blast from large charges so that the highest frequency components which must be transmitted by a long cable are relatively low. Consequently cable termination is often unnecessary, provided the amplifier will not respond to the resonant frequencies of the cable. If the amplifier response is too high at the resonant frequencies, it is necessary either to terminate the cable or to connect a low-pass filter to the amplifier. Since the terminating condenser C_s is likely to attenuate all frequencies of the gauge signal more than a filter, the latter is to be preferred.

(b) Termination of preamplifier output cables. -- Matching of preamplifier output cables requires that the preamplifier have an output impedance of approximately the same magnitude as the characteristic impedance of the line. Because it is not possible to use transformers for coupling to the cable, since they do not satisfy the low-frequency requirements, it is customary to use a cathode follower for the output stage of the preamplifier.

Resistance termination of cables is described in standard texts on transmission lines [31, 32]. Usually the receiving end of the cable is terminated with a resistance equal to the characteristic impedance of the line, which, for coaxial cables, generally is not over 70 to 100 ohms. No standing waves are set up in the cable under these conditions, but since the required value of the terminating resistance is smaller than the minimum value of self-bias resistance that can be used with most receiving tubes, additional bias is required in the cathode follower stage.

If a high impedance termination is used at the receiving end of the line and the transmitting end (the cathode follower) is adjusted to have an output impedance equal to the characteristic impedance of the cable, it is possible to use a larger cathode resistance and additional bias is unnecessary. The output voltage of the second system is larger than the first by the factor $(1 + g_m R)$ where g_m is the transconductance of the cathode follower and R is the characteristic impedance of the line. Under these conditions, standing waves are set up, but the transmission is still independent of frequency, as can be seen from inspection of the reflection coefficients, up to the frequency where the cathode follower becomes nonlinear.

When the receiving end is terminated, the load of the cable on the cathode follower is purely resistive; but when an open-circuited receiving end is used, the load is capacitative up to quarter-wave length. The load approaches a short circuit at quarter-wave length, then is inductive up to half-wave length; it approaches an open circuit at half-wave length, then becomes capacitative, and so forth. Distortion occurs in the cathode follower due to the small value of the load and the phase shift introduced by the load between the grid and the cathode of the tube, so that this method is good only at frequencies below those corresponding to the quarter-wave length of the line. A combination of these two systems, using an approximate termination at both ends of the cable, is also possible but in any of these arrangements the maximum linear voltage swing from the cathode follower is small.

If the high-frequency response is not too high, filters can be profitably used in this circuit, as in the gauge cable circuit, instead of cable terminations.

Termination at the receiving end was used with 600 ft of RG-11/U [18] and termination in the cathode follower was employed with 800 ft of RG-11/U [25]. Although neither system was investigated thoroughly, the response to a unit step appeared to be satisfactory.

Chapter 5

AMPLIFIERS

Amplifiers for use in equipment for the measurement of air-blast with piezoelectric gauges are discussed in the following. This chapter also includes a discussion of the requirements imposed on these amplifiers; a comparison of the merits of field preamplifiers and amplifiers for use with long gauge cables; and a description of the amplifier circuits used at UERL. Methods for testing amplifier characteristics and some of the circuits which form the basis of these amplifiers are discussed in more detail in Appendix B.

5.1. Amplifier requirements

(a) Sensitivity. -- The gain required in an amplifier depends on (i) the level of pressure to be measured, (ii) the gauge sensitivity, (iii) the capacity in the gauge circuit, (iv) the deflection factor of the cathode-ray tube, and (v) the deflection required for accurate measurement of the records. The maximum gauge sensitivity available, as indicated in Chap. 3, is about 100 $\mu\mu$coulomb/(lb/in^2). The minimum capacity C which can be used in the gauge circuit is determined by the time-constant RC required to give adequate low-frequency response [see Sec. 1.1(d)] and by the leakage resistance R; and the maximum capacity is governed by the length of the gauge cable, which is determined by the location of the equipment. The cathode-ray tubes usually used have a deflection factor of 50 to 70 volts/in. and the minimum deflection necessary with the cameras and measuring system employed at UERL is 1 to 2 in. The highest voltage gain available in UERL amplifiers is about 96 db (60,000 times) which corresponds to a sensitivity of 2 mv for the standard 2-in. deflection which is required with the cameras used. This gain is sufficient for measurements at somewhat less than 1 lb/in^2 with 1000 ft. of Tolconax cable terminated for high frequencies, but higher sensitivities are sometimes required.

The sensitivity should be stable over a period of 5 to 10 min and should not change appreciably over longer periods. Four kinds of gain-instability have been encountered: (1) a slow drift in sensitivity, (2) a random and rapid variation in gain, (3) large, but infrequent gain changes of short duration, and (4) a dependence of gain on the time between successive application of signals to the amplifier. Although drift can usually be eliminated, the causes of the other types of instability are not understood.

Although the over-all sensitivity of the recording system can be controlled by using padding capacity in the gauge circuit, it is more convenient to include a gain control in the amplifier. Gain controls should not affect the high-frequency response or other amplifier characteristics.

(b) Linearity. -- It is necessary that the amplifier be linear over the entire range of deflection and sensitivity for which it is to be used, but the linearity requirements are somewhat reduced by using the step-amplitude calibration described in Chap. 9. In the UERL equipment for measuring air blast the step amplitude is adjusted to be within 3 db of the amplitude of the peak pressure signal, and since the step deflection is also affected by the nonlinearity, the error in the peak pressure and positive impulse will be less than the deviation of the sensitivity of the system from linearity. Thus the error in peak pressure due to nonlinearity is about 40 percent of the nonlinearity in the system, and the error in positive impulse is 70 percent of this nonlinearity. It is preferable to use a step deflection 3 db lower than the peak deflection rather than 3 db higher.

(c) Frequency response. — The frequency response required in an amplifier is determined by the characteristics of the pressure-time curves to be recorded, by the high-frequency response of the gauge, and by the time constant in the gauge circuit. At this laboratory high-frequency response is usually evaluated in terms of the sinusoidal frequency at which the response is down 3 db (30 percent) from its mid-frequency value and low-frequency response is measured in terms of the decay of a unit step, although not necessarily in terms of the time constant of its decay. Calculation of the response requirements can be made from the equations given in Chap. 1.

(i) High-frequency response. The high-frequency response of an amplifier is limited by stray capacity shunting the load resistors and by loading in the output circuits. These effects are sometimes partially counteracted by using high-frequency compensation networks between the stages of the amplifier and by employing cathode followers in the output stage. The output loading in field preamplifiers is a transmission-line problem and is discussed in Sec. 4.3.

The high-frequency response available in UERL amplifiers used for air-blast measurements is down 3 db (30 percent) at from 60 to 100 kc/sec. Although this response is adequate for the majority of pressure measurements, better response is required if measurements of the peak pressure are to be made (with a distortion of less than 1 percent) from small point charges (2 lb) and small line charges (0.1 lb/ft) at pressures greater than 50 lb/in^2.

(ii) Low-frequency response. The low-frequency response of an amplifier for use with piezoelectric gauges is limited by its input resistance, which affects the time constant of the gauge circuit, and by the coupling circuits between the stages of the amplifier.

Ordinarily the resistance of the gauge circuit is limited by leakage in the gauge, cables, and connectors to a value of 500 megohms or less, so that it is unnecessary to have an amplifier input resistance above 500 to 1000 megohms. A higher leakage resistance is advantageous (see Sec. 5.2) when field preamplifiers are used so that if, by employing special precautions, the cable and gauge leakages can be maintained at values higher than 1000 megohms, it is important to have very high amplifier input resistances. The highest amplifier input resistance used at UERL is 1000 megohms, but higher resistance can be obtained with electrometer tubes. Whenever the cable capacity and the leakage resistance in the gauge circuit are too small to provide an adequate time constant, additional capacity must be added, with a consequent loss in sensitivity.

Amplifiers for use in air-blast measurements are either of the direct-coupled type, which do not cause low-frequency attenuation, or of the resistance-capacitance coupled type, which have a finite time-constant. The output of an amplifier containing n resistance-capacitance coupled stages with time constants λ_1, λ_2--- λ_n, respectively, is equivalent, at times short compared with the over-all time constant of the amplifier, to a single resistance-capacitance coupled stage with a time constant

$$\lambda = \frac{(\lambda_1)(\lambda_2)---(\lambda_n)}{\lambda_1 + \lambda_2 +---+ \lambda_n} \qquad (5.1)$$

which is considerably smaller than the time constant of the individual stages. Since low-frequency compensation is frequently used, the low-frequency response cannot always be expressed as a simple over-all time constant (see Appendix B).

The best low-frequency response available in UERL amplifiers is sufficient for recording the positive impulse from a pressure-time curve of 60 msec duration with an error of less than 1 percent. This is the positive duration of a pressure-time curve from a 10,000-lb bomb at 3 lb/in^2.

(d) Centering circuits. -- When a low-frequency amplifier is used, the connection between the cathode-ray tube and the amplifier is most logically direct-coupled. This requires that a centering circuit be included in one of the amplifier stages.

The standard procedure of recording at UERL is to photograph one or more calibration steps and a timing calibration on one film and if the individual traces are not to interfere with one another on the film, it is necessary that they be displaced from each other between successive exposures. Displacement circuits, which provide a fixed displacement between exposures, are built into the UERL amplifiers and are controlled automatically when the master control (see Chap. 10) selects the operation to be photographed.

(e) Freedom from spurious signals. -- Spurious signals are likely to occur from three sources: (1) They may be inherently present in the amplifier and power supply. (2) They may be caused by the presence and interaction of other electronic equipment. (3) They may be picked up or produced in the field. Amplifiers are required to be free from spurious signals from the first and second source, but signals from the third source cannot usually be eliminated by amplifier design. The most important types of spurious signals from the first two sources are:

(i) Line-frequency pickup, usually 60 or 120 cps. In the measurement of positive impulse 60 cps pickup introduces an error that is a maximum for pressure-time curves with a positive duration of about 8 msec. The maximum error in the impulse under these conditions is twice the relative amplitudes of the pickup and the pressure signal. Thus when the 60 cps ripple has a peak-to-peak amplitude on the cathode-ray tube screen of 0.1 in., and when the peak height is 2 in. and the positive duration is 8 msec., the error in the positive impulse is 10 percent.

(ii) High-frequency hash and thermal noise. This type of signal is not usually apparent on the photograph of a single oscillograph trace even when it is very noticeable on continuous sweep.

(iii) Cross talk between recording channels or between amplifiers and the supplementary equipment.

(iv) Line-voltage fluctuations which occur normally during operation. These variations should not produce any spurious signals or affect the operation or gain of the amplifiers.

(v) Drift, that is, steady changes in position of the cathode-ray tube trace or steady changes in the operating conditions of the amplifier stages. Drift, even when very slight, can cause errors in the measurement of positive impulse because it introduces an uncertainty in the zero-line on the oscillogram. If the drift is large during the interval between the setting of the trace position and the recording, the record may occur when the trace is at the edges of the cathode-ray-tube screen, which is a position in which the amplifiers and the cathode-ray tubes are not linear.

(vi) Spot instability, that is, randomly occurring motion of the cathode-ray tube spot. Spot instability, even when very slight, can introduce the same uncertainty in the zero-line as is introduced by drift.

(vii) Oscillations and motorboating.

(viii) Microphonics, which should be small enough not to cause the records to be obscured in any way. The sensitivity to microphonics which is permissible depends on the amount of noise to which the amplifiers are usually subjected: field preamplifiers have to withstand fragment bow-waves, ground shock, and in some cases the blast wave itself, while most other amplifiers are exposed only to vibration from motors and the noise in the operating room, which is usually from fans, intercommunication systems, and so forth.

The presence of spurious signals limits the maximum sensitivity of the amplifiers and the different types of signal have not always been successfully eliminated. The use of push-pull amplifiers and construction of the equipment in such a way as to permit flexibility in the choice of ground connections are invaluable aids in eliminating spurious signals, particularly those originating in the field.

(f) Reliability and simplicity. -- Amplifiers must be reliable, rugged, easily serviced, and independent of weather conditions, as has been indicated in Chap. 1.

5.2. Comparison of amplifier systems

The distance from the explosion of a small charge which is safe for the location of the cathode-ray tubes, cameras, control equipment and operating personnel may be as little as 100 ft, but the distance required between a 10,000-lb bomb and the control point is 1000 to 1100 ft. The safe distance from an atomic bomb seems to be 6 to 20 miles. Two amplifier systems, excluding those involving wireless transmission, are possible for use with piezoelectric gauges: (1) All stages of the amplifiers can be located at the control point, in which case the length of cable in the gauge circuit is determined by the distance between the gauge and the control point. (2) All or part of the amplifier stages can be located in the field. With this arrangement a short cable is used in the gauge circuit and a long low-impedance cable connects the field preamplifiers to the major part of the recording equipment, which is located with the operating personnel. The low-impedance cable does not reduce the strength of the gauge signal.

Assuming that it is possible to design both types of amplifiers, the following comparisons can be made between the two systems:

(a) Sensitivity. — The gain necessary in field preamplifiers, if they are far enough behind the gauge not to be struck directly by the blast for the duration of the recording, is as much as 10 times less than the gain required in amplifiers used at the control point and is even less if the preamplifiers are placed closer to the gauge. Whenever distances of more than a few thousand feet are necessary between the gauges and the operating personnel, the gain required in an amplifier located at the control point would have to be too high to be practical. Field preamplifiers offer relatively little advantage for small-charge measurements because the gauges are usually used near the personnel and the major part of the equipment.

(b) Frequency response. — The high-frequency-response problems of the amplifiers are not particularly troublesome in either type of system. When long gauge lines are employed it is necessary to terminate the gauge cables, but the length of cable and upper frequency for which termination is practical without introducing excessive attenuation is limited. When field preamplifiers are used, however, the cables leading to the control point have to be terminated, but for an ideal line with zero losses neither the length of line nor the frequency are limited. Since, for a field preamplifier to be of any advantage, the gauge cables used with it must be short, it is necessary, if the same value of the time-constant is to be maintained, to have higher leakage resistances in the cables used with field preamplifiers than in the longer lines. Because more stages are required in high-gain amplifiers, it is more difficult, on the other hand, to obtain as good a low-frequency response in high-gain amplifiers as in the lower gain field-preamplifier system.

(c) Spurious signals. — A field-preamplifier system, involving shorter high-impedance cables and lower gain than the long-line system, would be expected to be less sensitive to spurious electrical signals than the latter system. Insensitivity to spurious signals is an extremely important consideration, for considerable time has sometimes been required, particularly when the equipment is set up in a new location, to eliminate external pickup from a high-gain system.

The main difficulty encountered in designing field preamplifiers is to make them sufficiently non-microphonic to be insensitive to fragment bow-waves and to ground shock. Whenever the preamplifiers are located close enough to the gauge to be struck by the blast before the pressure-time curve has been recorded, it is necessary for the preamplifiers to be insensitive to microphonics caused by the blast wave as well.

(d) Reliability, simplicity and convenience of operation. — Operation of field preamplifiers is more difficult than operation of high-gain amplifiers. Field preamplifiers are more sensitive to damage from fragment hits not only because the amplifiers are exposed to the blast, but also because additional cables are needed by the preamplifiers for control and, in some cases, for power. The servicing and general handling of field preamplifiers is more difficult than the servicing of the amplifiers used with long lines, particularly in bad weather.

The most serious problem in the design of field preamplifiers is the elimination of microphonics. Microphonics is caused by the blast wave, fragment bow-waves and ground shock, and except for the signal caused by ground shock, which can be eliminated easily by shock mounting, it is difficult to remove the microphonics completely. If the preamplifier is placed far enough behind the gauge, it will not be struck by the blast wave until the recording has been completed, so that the preamplifier need be insensitive only to the microphonics caused by fragment bow-waves and ground shock. Actually, unless very high impedances can be maintained in the gauge circuit, this system does not cause unnecessary signal attenuation, because the length of cable required is just adequate to provide a long enough time constant in the gauge circuit. Thus the distance travelled by the shock wave in a time somewhat longer than the positive duration of the pressure-time curve is, except at higher pressures, about equal to the length of cable with a capacity of 20 $\mu\mu$f/ft and a leakage resistance of 1000 megohms which is long enough not to introduce more than a 1 percent error in the positive impulse.

Receiving tubes are much too microphonic for use in a preamplifier which is exposed only to the fragment bow-waves during recording, and to design a successful field preamplifier either less microphonic tubes must be found or the preamplifier must be surrounded by soundproofing. Since complete soundproofing prevents ventilation, further difficulties are likely to be encountered, particularly since the cathode-follower output requires a power tube.

Field preamplifiers were used at Harvard University [18, 25], by personnel now at UERL. These preamplifiers were employed in two series of bomb tests, which were conducted at Aberdeen Proving Ground. They gave reasonably satisfactory results when employed for bare-charge measurements but were too microphonic to be successful for use with cased charges. (Actually the electrical characteristics of these preamplifiers, built at the beginning of the program of air-blast investigations by this group, were not as satisfactory as later amplifiers.) The cause of the microphonics was not correctly attributed to bow-waves from fragments until the end of the Aberdeen tests, and since that time very little additional investigation has been undertaken to solve the problem of microphonics, although enough preliminary work has been done at UERL to indicate that even tubes made especially for applications critical to microphonics, such as 1603's, require considerable soundproofing to be usable. The Ballistic Research Laboratory at Aberdeen developed a field preamplifier which consisted of two stages, one a 954 tube as a high-impedance input and the other a 955 tube as a low-impedance output. The preamplifier was enclosed in two concentric pipes buried in the ground. This preamplifier was employed successfully for a short time, but was discarded because of difficulties which were not considered fundamental: microphonic batteries and poor construction. (This information is a private communication from T. D. Carr and Phil Weiss of the Ballistic Research Laboratory.)

It is believed that a non-microphonic field preamplifier would be of considerable use in blast measurements and consequently a new program of investigation on this subject is being undertaken at UERL.

5.3. Circuits of amplifiers used at UERL

One of the two sets of amplifiers employed at UERL consists of a DuMont type 208 cathode-ray oscillograph which is used in conjunction with a preamplifier. The preamplifier, which is located within a few feet of the oscillograph, is used to provide additional gain and for connection to the gauge circuit, a high-resistance push-pull input. The other amplifier consists of a single unit, designed specially for air-blast measurements, which is included in the UERL Eight-Channel Mobile Laboratory.

(a) Preamplifiers. — The schematic circuit of the preamplifier now in use with the DuMont type 208 oscillograph is shown in Fig. 4. This preamplifier has a push-pull input, a single-ended output, and has a voltage gain of 40 to 45. The high-frequency response is down 30 percent at 80 kc/sec and the circuit is direct coupled. The input resistance is about 300 megohms and the output impedance is below 500 ohms. It is linear within 2 percent for input signals less than 0.75 DC v (see Appendix C for methods of measuring linearity).

The circuit consists of three stages: the first stage contains push-pull 6J7 cathode followers which provide the high input resistance; the second contains two push-pull 6SJ7's which provide gain and transfer between the signals on input conductor (1) and input conductor (2); the third stage consists of a single 6J5 which provides low output impedance.

The transfer of the signal between conductors is brought about, for the most part, by a large cathode resistor in the second stage and is aided to a slight extent by the first and second stage screen resistors common to both sides of the amplifier. The transfer is reduced somewhat by the small resistors in the individual cathode and screen circuits of the second stage; these provide a little degeneration and probably improve the gain stability. The output voltage is about 3 to 4 percent loss for a signal on conductor (1) than for an equal signal on conductor (2), so that the voltage applied to the 6J5 approximates, very closely, the output between the two plates of a conventional push-pull stage. The high-frequency response for signals applied to either grid is indistinguishable. The circuit is used for push-pull input signals and also for single-ended signals. When used for single-ended signals, one side of the amplifier input is grounded.

For frequencies up to 100 kc/sec the output impedance is sufficiently low to make negligible the effect of a capacitative load of 0.001 μf on the output. This capacity is equivalent to a microphone cable 20 to 25 ft long. The high-frequency response of the circuit is limited by the load resistor in the second stage.

Four preamplifiers are operated from a regulated power supply which is described in Sec. 11.3(b). Each preamplifier draws 14-15 ma plate-supply current between the positive and negative power-supply terminals. The tube heaters draw 1.5 DC amp per amplifier from a controlled circuit using a storage battery. [See Sec. 11.2(c)].

Details concerning the high input-resistance circuit, the transfer obtained in the second stage, the output impedance of the cathode follower, and the necessity of using a DC heater supply are presented in Appendix C.

In operation with the oscillograph the total usable sensitivity is about 3 DC mv for a 1-in. screen deflection. High gain is used in the preamplifier to enable the oscillograph to be run at low gain so that power supply ripple, instability, and hash, which are coupled directly from B+ through the 6SJ7 load resistor and the 6J5 to the oscillograph input, can be minimized. Operating the oscillograph at low gain also reduces the effect of ripple usually present in the input tube of the oscillograph. The magnitude of all spurious signals from the preamplifier and oscillograph combination is equivalent to an input signal of about 0.2 mv peak to peak.

Ninety-five times in 100 the deflection of a step calibration on the preamplifier and oscillograph combination differs from that of another step, applied within a minute, by less than 2 percent. Over a period of operation of one day the amplitude of 95 out of 100 steps differ from each other by less than 5 to 6 percent. The gain stability of the oscillograph is affected by line-voltage fluctuations and, unless a very stable line voltage is used, the changes in gain will be much greater than the figures given.

Tubes are usually preselected for use in this circuit. Balance in the second stage is difficult to obtain unless the currents of the tubes on either side of the amplifier are well matched. Recently a potentiometer has been added to the cathode circuit of the first stage to balance the cathode voltages, one has been added to the second stage cathode circuit to adjust the total cathode resistance, and one has been added to the second stage screen circuit to adjust the screen voltage. These potentiometer which are easy to adjust, greatly facilitate the alignment of the preamplifier. The tubes are also tested for microphonics and the 6J7's are tested for grid current.

Two preamplifiers are built on a 17X10X3 in. chassis with a standard 8-3/4 in. rack panel, although they could be built much more compactly. The two 6J7's and the input condensers are shielded by a sheet-metal cover and the chassis is reinforced with a wooden board one-inch thick which reduces microphonics. All connections are made to plugs in the rear of the chassis.

These preamplifiers have been in use continuously for over two years and have given reliable and satisfactory service.

(b) Amplifier in the DuMont type 208 oscillograph. — It has been possible to adapt the DuMont cathode-ray oscillograph, type 208, for air-blast measurements, by making slight alterations and using it in conjunction with preamplifiers. The characteristics of the vertical amplifier and the modifications made to it are discussed in this section; other modifications are described in Sec. 7.3(c).

The voltage gain of the unmodified amplifier is about 2000 and the sinusoidal frequency response is specified to be flat within ± 10 percent from 2 to 100,000 cps, although not all oscillographs from the factory have as good a high-frequency response as this. Two gain controls are provided and both the fine gain control and the centering control have a marked effect on the high-frequency response. The original circuit contains five stages: (1) A ½-6F8G input cathode follower, which is preceded by a 10-to-1 input-attenuator, that drives the fine gain control. (2) A ½-6F8G amplifier stage with high-and low-frequency compensation networks. (3) A second ½-6F8G amplifier, similar to the first. (4) A ½-6F8G cathode follower, which contains the centering control and drives the output tubes. (5) Two push-pull cathode-coupled 6V6's used to drive the cathode-ray tube through a high-resistance divider which lowers the mean DC output potential applied to the deflection plates to approximately zero volts. Resistance-capacitance-type coupling is used except between the 6F8 positioning tube and the 6V6's and between the cathode-ray tube and the 6V6's.

The modified schematic circuit is shown in Fig. 5. The modifications are: (1) Replacement of the continuously variable fine gain control by a step-wise control adjustable in 3 db steps. This required a change in the input-attenuator, to give maximum sensitivity coverage, from 10-to-1 to 60-to-1. (2) Complete rewiring of the input circuit, including the substitution of a 0.5 μf DYR oil-filled condenser for the paper tubular input-coupling condenser and the installation of General Radio jacks. (3) Moving the centering control from the cathode of T_4 to a divider from the +155 volt power supply to ground. This required a larger cathode resistor in T_5 and T_6 and a 0.05 μf by-pass condenser, connected from the grid of T_6 to ground. (4) Inclusion of a displacement circuit. (5) Removal of the 0.005 μf by-pass condenser in the cathode circuit of T_2. (6) Replacement of many of the

1 μf 200-v coupling condensers by 400-v condensers. (7) Adjustment of the input attenuator, compensating chokes and compensating condensers, which are usually not properly adjusted when shipped from the factory.

After making these modifications in the amplifier, the frequency response is down 3 db (30 percent) at 160 kc/sec at full gain on the fine attenuator and down 3 db at 120 kc/sec at step 7 on this attenuator, which is the attenuator setting which gives the poorest response. The step response is flat within $\pm$ 2 percent for 30 msec and the time constant is about 400 msec. The high-frequency response does not depend on the position of the centering control and the linearity is adequate for 1 to 1½ in. deflections on the cathode-ray tube.

The step-wise attenuator was inserted because it is generally found to be more satisfactory for use in blast measurements than a continuous control. Gain stability is affected by line-voltage fluctuations, which change the deflection sensitivity of the cathode-ray tube more than they affect the amplifier. The gain-stability of the oscillograph when connected to a pre-amplifier is described in Sec. 5.3(a).

The high-frequency response in the original unit is seriously affected by the resistance of the centering potentiometer, which is in series with the output impedance of the cathode follower (T_4). The response was improved by placing the centering control on a divider, as shown in the circuit diagram. A 0.05 μf condensor from the grid of T_6 to ground was necessary to eliminate the effect of the capacitative coupling between the long parallel grid leads to T_5 and T_6, which produced high-frequency peaking and made the response a function of the spot position. The by-pass condenser in T_2 was removed because it also caused peaking. The high-frequency response is limited by the coupling circuit to the cathode-ray tube and by the fine gain control. The effects of these two circuits are partially eliminated in DuMont oscillographs used for the study of underwater explosions at this laboratory [33], in which the high-frequency response obtained is flat within $\pm$ 2 percent to 300 kc/sec. The modifications in these oscillographs are made at the expense of sensitivity and convenience of operation.

Displacement is obtained by applying a voltage to the grid of T_6. The voltage is controlled by the master control (see Chap. 10) which contains a four-position-step switch for tapping voltages from a resistance divider connected across a 1.5 v battery.

Leakage in the coupling condensers has caused considerable trouble because it affects the low-frequency response, and frequently the value of the electrolytic low-frequency-compensation condensers has to be changed.

All oscillographs have a minimum residual hum of the harmonics and fundamental of 60 cps. In a properly operating oscillograph very little of this appears to come from the plate supply, which is adequately filtered and decoupled, or from the heater supply, except when the tubes in the first few stages have excessive heater-to-cathode leakage. The residual hum is from magnetic fields produced by the power transformer, which is picked up by the amplifiers and cathode-ray tube. The magnetic pickup seems to increase with the age of the oscillograph.

In addition, magnetic fields external to the oscillograph may cause considerable hum.

The trace of the cathode-ray tube is not too stable and usually drifts slowly back and forth with a maximum amplitude of about 0.05 in. except when the oscillograph is connected to a line with unsteady voltage, which will cause the spot to drift much more. If the continuous sweep is applied to the X-axis, it often couples into the Y-axis, and thus must be turned off during recording.

Microphonics is usually caused only by the first stage.

A larger number of oscillographs have been in service for from two to four years. Neither the fundamental design characteristics nor the mechanical and electrical construction are entirely satisfactory for blast measurements.

(c) Mobile-laboratory amplifier. -- The schematic circuit of the amplifier used in the Eight-Channel Mobile Laboratory is shown in Fig. 6. This amplifier was designed for air-blast measurements on charges weighing between ½ and 10,000 lb. Either single-ended or balanced gauge signals can be applied to the input and the output connects directly to the deflection plates of a cathode-ray tube.

The voltage gain of the amplifier is about 96 db (60,000), which corresponds to a deflection sensitivity of 0.7 to 1.0 DC mv/in. on the cathode-ray tubes at the accelerating voltages usually used. The high-frequency response at full gain is down 3 db (30 percent) at 100 kc/sec although it is somewhat better at low gains, and the response to a unit step is flat within -2 percent for 60 msec. (In present use the high frequency response is not this good; see the following.) The nominal input resistance is 1000 megohms and the output impedance can be lowered sufficiently to drive a cathode-ray tube without distortion when it is connected to the amplifier by no more than 6 ft of microphone cable. The amplifier is linear within 1.4 percent up to cathode-ray tube deflections of 4 in. It is provided with two gain controls which reduce the sensitivity in 1.5 db steps to a minimum gain of 46 db (200). A centering control and means of obtaining spot displacement are also included.

The amplifier consists of five push-pull stages which, except for one stage of compensated resistance-capacitance coupling, are direct coupled. The stages are: (1) A 6J7 cathode follower which provides high input resistance. (2) A 6SJ7 amplifier which includes the coarse gain control and low-frequency compensation. (3) A second 6SJ7 amplifier which contains the fine gain control. (4) A 6AG7 amplifier. (5) A 6SN7 cathode follower which provides low output impedance for driving the cathode-ray tube.

The gain is obtained primarily from the second 6SJ7 stage and from the 6AG7 stage, since the first 6SJ7 stage is operated at low plate current. The coarse gain control contains two equal steps which change the gain by 14 db (five times) each and one step which changes the gain by 6 db. The fine gain control contains 10 equal steps which change the gain by 1.5 db each. Stray capacity across the resistances in these gain controls can cause an increase in high-frequency response at low gain, and, although this effect can easily be avoided by careful layout, some of the units were constructed poorly and show high-frequency peaking at minimum gain.

The high-frequency response is limited about equally by the two 6SJ7 stages. The 0.25 μf oil condenser used for coupling between the second and third stages has to be insulated from the chassis to prevent excessive high-frequency attenuation, which is caused by the presence of shunt capacity (160 $\mu\mu$f) between the electrodes and the case of this condenser. The output stage has a sufficiently low impedance to drive a cathode-ray tube without distortion or attenuation up to 100 kc/sec when about 1 ft of single-conductor-microphone cable is used for connection to each deflection plate of the cathode-ray tube. When longer patch cords are used, phase shift between the cathode and grid of the output stage causes distortion of large amplitude signals at high frequencies, but by lowering the cathode resistance in this stage to 50,000 ohms the distortion is eliminated at frequencies below 100 kc/sec when patch cords up to 6 ft in length are used. (Single-conductor-patch cords are used to eliminate the capacitative loading between the two cathodes of the output.) In the circuit now in use the cathode resistors are 300,000 ohms and distortion appears at 20 to 30 kc/sec, although the distortion is masked by the attenuation of high frequencies brought about by the grounded can on the coupling condenser. The poor high-frequency response has been tolerated because in recent work good response at high frequencies was not required and the poor response permitted the use of long gauge cables without high-frequency termination.

The low-frequency response of the amplifier is limited by the compensated resistance-capacitance coupling between the second and third stages, which is designed and adjusted so that the step response will not decay by more than 2 percent in 60 msec and will not overshoot by more than 1 percent. The amplifier has a time constant of about 1.1 sec. The equations used in designing this stage are given in Appendix C. The adjustment has been found to be quite stable and is independent of tube variations.

The input resistance of the amplifier, which is nominally 1000 megohms, has never been measured directly under dynamic conditions, but in practice the time constant in the gauge circuit has not been limited by the amplifier-input resistance. The design of this stage is described in Appendix B.

A potentiometer in the plate circuit of the third stage provides centering. Four different displacement positions are obtained by shorting out combinations of the three 50 ohm resistors in this circuit. These resistors are connected to relays which are controlled by the master control (see Sec. 10.2(a)).

Four amplifiers are operated from one regulated power supply and draw 40 ma each between the positive and negative supply terminals. This power supply is described in Sec. 11.3(a). The tube heaters of the first three stages draw 1.8 DC amperes from a controlled storage battery circuit [see Sec. 11.2(c)]. One 10-amp transformer supplies heater current for the fourth and fifth stages of four amplifiers. The regulated power supply is not capable of delivering sufficient current to four amplifiers when they are used with 50,000 ohm cathode resistors in the output stage.

The output of the amplifiers at full gain is free from any noticeable hum but does contain a certain amount of high-frequency hash. The hash, the source of which may be in other electronic equipment in the Mobile Laboratory, is visible on continuous sweep but cannot usually be detected on the blast records. No short-time instability of the trace is observed.

Originally 600-v tubular wax-filled paper condensers were used for coupling between the second and third stages, but it was found that leakage in them caused considerable drift. These condensers were replaced by 2000-v oil-filled condensers and, although some drift probably exists, it has never been marked enough to cause any concern during operation. It is necessary to allow the amplifiers a warmup period of about a half hour in order to allow the long-time-constant input circuit to come to equilibrium.

Ninety-five times in 100 the deflection of a step calibration on the amplifier differs from that of another step applied within less than five minutes by less than 3 percent. Over a period of operation of one day, 95 out of 100 steps differ from each other by less than 5 to 6 percent.

The circuit has required selection of tubes free from microphonics and with matched plate and screen currents. The procedure in lining up the amplifier is first to select two tubes for the first stage which will produce cathode voltages within a few tenths of a volt of each other. (It is planned to insert a potentiometer in the cathode circuit of this stage to facilitate balancing of the cathode voltages.) Potentiometer R_4 (R_4 should be increased above the value indicated in the circuit to permit sufficient control) is then adjusted to obtain equal plate voltages on the second stage with R_1 set for minimum gain (maximum resistance between cathodes). Potentiometer R_6 is adjusted with R_2 set at full gain (no resistance between cathodes) until the plate voltage of the third stage is correct, and then R_5 is adjusted until no change in plate voltage occurs when R_2 is varied from maximum to minimum gain. (It is planned to insert a potentiometer in the screen circuit of the third stage to make these adjustments easier.) Some difficulty has been encountered in making these adjustments unless the tubes on the two sides of the circuit are well matched, but it is hoped that the inclusion of the two additional potentiometers will simplify the alignment. Potentiometer R_5 was placed on the panel but frequent adjustment has not been found necessary. The adjustments do not usually have to be checked more frequently than once every three months of continuous operation.

The main difficulties with these amplifiers have been caused by microphonic tubes and drift in components. It is important to minimize the voltage across carbon resistors to prevent drift, and before two series 150,000-ohm resistors were inserted in place of a single 300,000-ohm resistor, considerable trouble was encountered from this source in the screen of the third stage. The effect of drift in this screen resistor can probably be reduced by connecting it to ground instead of to B+, but this has not been tried. Although the tube emission becomes lower with use, low emission has not caused appreciable trouble.

Two amplifiers are built on a 17X13X3 in. chassis with a standard 7-in. rack panel. The first two stages and the input condensers are shielded by a sheet metal cover. All connections are made by plugs at the rear of the chassis and circuit grounds are insulated from the chassis. Two double-pole relays are used for spot displacement in one pair of amplifiers.

Eight of these amplifiers have been in constant use for a year and a half and have given satisfactory service, although, as indicated above, certain modifications are planned.

Chapter 6

TIME BASES, BEAM-BRIGHTENERS, AND SYNCHRONIZATION

In the recording of transients on a cathode-ray tube, time resolution is obtained with either a sweep-generator, which deflects the cathode-ray tube spot and is synchronized with the occurrence of the transient, or by moving the photographic film used for recording. The intensity of the beam on the tube is also synchronized with the transient by an electronic beam-brightener.

6.1. Requirements of time bases and associated equipment

(a) Linearity. — Direct measurement of the pressure-time curve requires a linear and uniform time base. Instantaneous fluctuations in the speed of the time base as well as uniform changes in speed during recording must be eliminated. The instantaneous fluctuations can be caused by frequency modulation of the trace, irregularities on the face of the cathode-ray tube, mechanical vibration in moving-film cameras, and so forth.

(b) Resolution and speed. — It has been found convenient in the recording of the usual type of pressure-time curves to adjust the time base so that the deflection on the photograph corresponding to the positive duration of the pressure-time curve is approximately equal to the maximum deflection corresponding to the peak pressure. Measurement of shock velocities, however, requires greater resolution.

The zero line preceding the shock wave and fragment bow-waves on a photograph of a pressure-time curve, which serves as a line of reference on the pressure axis, should be long enough to permit, during the measurement of the record, an accurate extrapolation past the point on the photograph corresponding to the positive duration. It should be noted that, if fragments precede the shock front, a longer zero line is required. In addition, the photograph ordinarily includes a short interval after the positive duration. These considerations determine the duration of the time base.

(c) Beam brightening. — The intensity of the cathode-ray tube spot must be uniform while the recording is being made and, to prevent film fogging, it is usually required to be extinguished at all other times. Rapid mechanical shutters are, in general, impractical except for moving-film cameras with continuous film or for very slow recording.

(d) Synchronization. — The time interval over which the synchronization must operate and the accuracy of its timing depend on the type of time base employed. When a single-sweep generator is employed, both the initiation of the sweep and the beginning of the beam brightening are synchronized with the phenomenon under observation, and the beam is usually extinguished at the end of the sweep. When rotating-drum cameras are used, the camera motor is started at some time previous to the occurrence of the phenomenon to be recorded so that, although the motion of the drum need not be synchronized, the initiation of the beam brightening has to be synchronized with the recording and, to prevent successive traces on the film from overlapping, the beam intensity has to be extinguished before one complete rotation of the drum has elapsed. In some cases the drums are synchronized with the transient to avoid the blind spot at the ends of the film. Moving-film cameras are turned on by hand or by a simple sequence timing device and do not require careful synchronization of either the camera or the beam intensity.

6.2. Comparison of sweep-generators and moving-film time bases

(a) Sweep-generators. — The advantages of a sweep-generator fixed-film camera system are: (1) The fixed-film cameras are relatively compact, contain a minimum of moving parts and do not require power for operation. (2) The photographic processing such as preparation of the film and loading and developing are comparatively easy to perform. (3) The analysis of records from fixed-film cameras can usually be accomplished more rapidly than those from moving-film cameras. (4) By observing the cathode-ray tube screen during the recording of the oscillogram, a completely resolved view of the pressure-time curve can be obtained.

The disadvantages are: (1) The time base is electronic and cannot, in general, be made as linear or as stable as those obtained by the use of moving-film cameras, and the output of a sweep-generator is likely to contain instantaneous fluctuations in speed. It is not advisable to calibrate the time base simultaneously with the recording of the phenomena under study because simultaneous timing marks would interfere with the record, particularly in the peak region of the pressure-time curve. Thus a high degree of stability is necessary in a single-sweep time base. (2) Certain distortions in the cathode-ray tube and others which are inherent in the photography of curved screen tubes [see Sec. 7.2(b)] affect the measurement of positive impulse and positive duration. These distortions and the decrease in the quality of the focus of the trace are of importance only when large sweep deflections are used. One of these distortions, which is troublesome on records obtained with single-sweeps, is an occasional curvature of the trace. The trace should, of course, appear as a straight line on the photograph when no signal is applied to the signal axis, but this has not always been the case. The cause of this distortion has not been determined. (3) The stability of the time base depends on both the stability of the deflection sensitivity of the cathode-ray tube and on the constancy of the speed of the sweep-generator. (4) The resolution obtainable with sweep-generators for a given sweep duration is limited by the size of the cathode-ray tube and, although with 5-in. tubes the resolution is adequate for ordinary blast records, the length of the sweep is too short to obtain both adequate resolution and a baseline long enough for extrapolation on records of pressure-time curves from cased charges, and is not sufficient for measurements of shock velocity.

Sweep-generators are used whenever compactness, convenience, and speed of operation are important. They are not as precise as moving-film-type time bases.

(b) Moving-film-time bases. Two types of moving-film cameras are used for oscillograph photography: rotating-drum cameras, which necessarily have a blind spot where the ends of the film are butted or overlapped, and continuous-film cameras. The advantages of both of these cameras, which have certain characteristics in common, are: (1) They provide an accurate linear time base which can be calibrated simultaneously with the recording of the phenomena under observation. Certain types of nonlinearity may occur when moving-film cameras are used. The most common sources of nonuniformity are: (i) spurious motion of the cathode-ray-tube spot in the direction of motion of the film; (ii) mechanical vibration such as gear chatter; (iii) gradual speed changes in the driving motor; and (iv) film buckling. The first source of difficulty can be removed by proper shielding of the cathode-ray tube and by connecting to ground, either directly or through a low impedance, the deflection plates of the tube that are not used for the signal. The other sources of nonuniformity can usually be made small, but in any case they are included in the timing calibration applied at the same time the record is photographed. (2) Since only signal axis deflections are used, cathode-ray tube and photographic distortions are kept to a minimum. (3) The resolution which can be obtained on moving-film cameras is much greater than which is available when fixed-film cameras are used. The writing speed of a continuously moving-film type of camera is limited, in practice, by the intensity of the cathode-ray tube. The long base-line which can be used when moving-film cameras are employed is extremely useful for the measurement of blast from cased charges.

The disadvantages of moving-film cameras are: (1) The cameras are more bulky and more complicated than fixed-film cameras. (2) They require motors and power. (3) Film-speed control is much more complicated than speed control in electronic sweep-generators. (4) Cutting, loading and general processing and preparation of the film is more difficult than for film used with fixed-film cameras. (5) Analysis of records is usually slower than for fixed-film cameras. (6) A completely resolved visual picture of the record cannot, in general be obtained before the films are developed [however, see Sec. 8.4(c)].

Thus moving-film cameras are used when the most accurate results are required, when the blast from cased charges is measured, and when problems are investigated which require higher resolution than is necessary for the photography of pressure-time curves.

The operation of rotating-drum cameras is more convenient than the operation of continuous film cameras, since the rotating-drum film is short and consequently can be processed more readily. Short film is almost a necessity when the records have to be examined after each experiment and continuous-film cameras consume up to 10 times the film used with drum cameras. Continuous-film cameras, however, can be daylight-loaded, a convenience not readily adapted to drum cameras. The most serious disadvantage of drum cameras is the blind spot on the drum at the two ends of the film. The width of this blind spot can be reduced by using the proper film catches, but when a slight chance of losing a record because of this blind spot cannot be tolerated, a system of synchronization of the explosion with the drum position must be used, which increases considerably the difficulties of synchronization.

At this laboratory drum cameras are considered to be more practical for general use than are continuous-film cameras.

6.3. Methods of obtaining synchronization

The time at which sweep-generators and beam-brighteners are started is referred either to the current used to initiate the charge or to the explosion itself, although, in some cases, when rotating-drum cameras are used, the detonating current is synchronized with the position of the film drum. Ordinarily, step-generators for providing calibration steps [see Sec. 10.2(c)] trip the sweep-generators and beam-brighteners directly but they also may be synchronized with the position of the film drum. Only the beam intensity has to be synchronized with the detonation when rotating-drum cameras are used because the cameras are brought up to speed for a considerable length of time before detonating the charge.

(a) Synchronization methods referred to the explosion or to the detonating current. — (i) Synchronization with pressure switches. A very simple method of synchronization uses a blast-operated switch, placed between the gauge and the charge, that is actuated when struck by the pressure wave. A typical switch of this type, known as a tripper, is shown in Fig. 7. The sweep-generator or beam-brightener is tripped when the contact made by the movable metal flap and the setscrew is broken, which occurs when the flap is struck by the blast wave. Both contacts on the tripper are insulated from the mounting so that they can be grounded or not at will.

The time between the initiation of the beam and the start of the blast record is determined by the distance between the tripper and the gauge, and by the speed of the shock wave. If gauges are placed at different distances from the charge, it is sometimes necessary, in order to obtain sufficient resolution of the pressure-time curve when using single-sweep generators, to have a different sweep speed and, therefore, a different sweep-generator, for each distance. Frequently the sweeps have to be initiated at different times, which may be done either with more than one tripper, placed at different distances from the charge, or with one tripper and an electronic delay circuit. Except in the very first experiments at this laboratory, electronic delay circuits have not been used in equipment for air-blast measurements, but a satisfactory circuit has been developed for underwater shock-wave studies [33].

These trippers have been used successfully at pressures from 1 to 100 lb/in^2, but difficulty is encountered outside this range. At lower pressures the sensitivity of the tripper, which is determined by the adjustment of the setscrew contact, and by the elastic force constant and area of the metal flap, must be so high that strong winds are likely to open the circuit and the action of the tripper is no longer reproducible. At high pressures the conducting flame from the explosion maintains a conducting path across the opened contacts of the tripper and no pulse is obtained.

The use of a tripper on experiments with cased charges requires additional precautions because, since the fragments from the case precede the blast wave, a fragment or its accompanying bow-wave may open the tripper prematurely. This can usually be prevented by placing more than one tripper in parallel, separated from each other by about 10 ft and at the same distance from the charge, and by erecting a barricade a few feet in front of each tripper. The cables to the tripper should be protected from direct fragment hits.

(ii) Synchronization with pressure gauges. A similar method of synchronization consists of using a pressure gauge such as a piezoelectric gauge or a geophysical seismometer which generates a signal when struck by the blast. The sensitivity requirements may necessitate amplification. This method has not been used at this laboratory.

(iii) Synchronization by the breaking of wires located at the explosion. Either a wire wrapped around the charge or the bridge wire in the blasting cap is broken by the detonation of the explosive and the breaking of either of these wires has been used to provide a synchronization signal. Neither method is reliable because the conducting flame from the explosion maintains a continuous electrical circuit across the wires even when they are broken.

(iv) Synchronization by controlled switching. A reliable method for use at both extremes of pressure and for tests on cased charges refers the initiation of the beam brightening to the time of closing the firing switch. One of the simplest ways of doing this involves the use of a double-pole double-throw relay. One pole of the relay is connected to the beam-brightener circuit and is normally closed; the other, which is normally open, is connected in series with the detonator and firing battery. A two-pole relay is used in order to isolate the two circuits from each other. Energizing the relay first opens the beam-brightener circuit, which turns on the beams, and then closes the firing circuit, detonating the charge. The time between the initiation of the beams and the start of the record depends on the delay in the relay, the time delay in the detonator, and the time required for the blast wave to travel from the charge to the gauges. The relay may take as long as 2 to 30 msec from the opening of one pair of contacts to the closing of the others, but for a given circuit this delay, which depends on the type of relay and the energizing circuit, is reasonably reproducible. A double-pole switch can also be used if it is spring-actuated so that the time delay does not depend on the speed with which the switch is closed. The delay in the detonator may be made quite small if a large enough current is used, and thus with seismographic, regular No. 8 or U.S. Army Engineer's Special blasting caps the delay has not been long enough to cause any difficulty.

A relay cannot usually be used with single-sweep circuits because the delay between initiation of the sweep and the start of the record is too long, but either mechanical, electromechanical, or electronic time-delay switching circuits can be employed. A biologist's spring rheotome has been used at this laboratory. This device, shown in Fig. 8, consists of a long flat spring and two or more contacts. The spring is first cocked and the contact pins closed; on releasing the spring it swings through an arc, striking one contact pin after another. The time delay is determined by the distance between contact arms on the arc traversed by the end of the spring and by the period of the spring, which may readily be changed by adding weights to it. The contact pins can be used to either make or break a circuit so that considerable versatility is possible. Delays of 1 msec to 150 msec have been obtained, with a reproducibility of about 1 percent, on the rheotomes made by the Marine Biological Laboratories. At the British Armament Research Department a pendulum serves the same purpose as the spring rheotome. Electronic delay circuits are used for underwater investigations at UERL [33]; an electronic sequence timer is used for air-blast measurements [34] at Princeton University; and a motor-driven sequence control is used by the Stanolind Oil and Gas Company [20].

(v) Synchronization by the flash from the explosion. Another possible method of synchronization, which is still in the design stage, uses the light from the explosion to energize a photoelectric cell focused on the charge from a considerable distance. This method does not require the use of any electrical circuits near the conducting flame from the explosion so that it might eliminate pickup from electrical disturbances accompanying the detonation.

(b) Synchronization methods referred to the drum orientation. — When rotating-drum cameras are used, it is often advantageous to synchronize the explosion with the position of the drums both to prevent the loss of records across the blind spot and to facilitate the measurement of records by always locating the pressure-time curve and the calibration steps at a preassigned position on the film. Exact synchronization of the pressure records to appear at preassigned positions on the film is not possible when more than one drum is used unless the orientation of each drum relative to the others is fixed by mechanical or electrical (selsyn) interlocking [see Sec. 8.4(a)]. It is possible, however, to provide approximate synchronization, sufficient to prevent any part of the pressure-time curve from occurring on the blind spot, when there are two independent groups of drums. This method is not applicable when the pressure-time curve occupies an appreciable portion of the film length. These methods of synchronization are discussed in the following.

(i) Exact drum synchronization. When all drums are interlocked with each other, synchronization is accomplished by obtaining a pulse from a rotating switch which makes contact at only one orientation of the drum. The rotating part of this switch is an insulated disk which can be attached to the drum shaft in any orientation and which contains two metal contacts electrically connected to each other, as shown in Fig. 9. The stationary parts of the switch are two phosphor bronze wires, serving as brushes, which ride in a groove cut in the edge of the disk. The two metal contacts close the circuit between the wires once each revolution of the shaft, thus giving a pulse which can be oriented at any desired position relative to the break in the film. This pulse is of too short a duration to close a relay for detonating the charge so that it is first used to trip the thyratron circuit shown in Fig. 9.

The operations switch, shown in the figure, is used to control this circuit. When the thyratron is fired, which occurs when the operations switch and the rotating switch attached to the drum shaft are simultaneously closed, the relays are closed and the charge is detonated. Once fired, the circuit will continue to conduct as long as the operations switch is closed because, within wide limits, the current in a conducting thyratron is independent of the grid bias. In the particular circuit shown, the plate-circuit relay is used to actuate another heavier contact relay, which trips the beam and detonates the charge. The switch is isolated from the camera shaft to avoid ground loops between the tripping circuit and the signal circuits, which are connected to the tripping-circuit ground in the master control [see Sec. 10.2(a)]. In order to synchronize calibration steps with the drum position, the step-generator [see Sec. 10.2(c)] is connected into the relay in place of the beam-brightener circuit and the firing circuit is disconnected.

This synchronizing device has proven quite reliable, during limited use, on drum speeds up to 1 revolution in 50 msec, which is the fastest speed at which it has been tested. Although this unit has been satisfactory, the mechanical and electrical details shown in the figure were used for the original experimental model and certain modifications are probably in order if a permanent unit is to be constructed.

(ii) Approximate synchronization. When two drum shafts are belt-driven, a synchronization pulse is obtained by placing a rotating switch on both shafts and connecting the switches in series. These switches, shown in Fig. 10, are each made up of two (formica) disks, in the shape of a half sector, which actuate a type B-RS microswitch by means of a type JR actuator. The microswitches are connected in series and to the hold-down relay in the circuit, which controls another relay connected in the beam-brightening and firing circuits. The interval between the closing of the operations switch and the simultaneous closing of both the rotating switches is, in general, quite long unless contact is made over a considerable fraction of the period of rotation of each shaft, and this, of course, prevents exact synchronization with the blind spot on the drum. The two sectors on each shaft can be rotated with respect to each other so that the duration of contact may be varied from zero to one half the period of rotation.

The rotating sectors have been used successfully at speeds corresponding to from 50 to 500 msec per revolution but, while slower speeds have not been tried, at faster speeds the switches make considerable noise, causing microphonics in the amplifiers, and the duration of contact is too short to close the hold-down relay. Smoothly riding contacts, similar to those shown in Fig. 9, should prevent excessive noise and the thyratron circuit could be used instead of the hold-down relay, since it will respond more rapidly than the relay.

6.4. Sweep-generators*

(a) General considerations relating to the design of sweep-generators. — Single-sweep circuits used for the photography of pressure-time curves are required to be linear and should cause only a minimum of defocusing of the cathode-ray tube. They must include beam brightening and it is necessary to incorporate a tripping circuit which can be connected into the synchronization circuit.

(i) Linearity. The sweep voltage in UERL sweep-generators is obtained from the small linear portion of the charging or discharging voltage of a series resistance-capacity circuit. In one type of circuit a voltage is fed back to the generating circuit to compensate for deviations from linearity, but most of the circuits use a triode or pentode with a large unbypassed cathode resistor, which provides a high dynamic series resistance without an excessively large supply voltage. The dynamic plate resistance of these tubes is $[r_p + (1 + \mu) R_c]$ where r_p and μ are the plate resistance and amplification factor of the tube, respectively, and R_c is the unbypassed cathode resistance. Puckle has written an excellent book on time bases and trigger circuits in which these considerations are discussed in detail [35].

A photograph of a sweep trace on a cathode-ray tube with timing marks applied to the signal axis is measured with an optical comparator in order to determine the linearity of the trace. The timing marks are short-duration spikes obtained by differentiating a square wave [see Sec. 9.3(b)], and the frequency so that the marks appear close together. It has been found that the linearity, that is, the change in velocity of the cathode-ray-tube spot over the entire sweep, in sweeps similar to the circuit of Fig. 11 in Sec. 6.4(b), is so small that it is difficult to measure, that the apparent linearity may depend more on the cathode-ray tube and camera than on the sweep-generator, and that there appear to be small random variations in the spot velocity which are greater than the change in velocity from one end of the sweep to the other. These small variations are usually hard to detect and may be within the experimental errors of measurement.

Usually the main source of nonuniformity in the sweep output itself, as distinguished from irregularities occurring in the cathode-ray tube, is line-frequency modulation of the sweep velocity. Dielectric absorption in the speed determining condensers can also be a source of nonlinearity.

(ii) Defocusing. The focus at the edges of a cathode-ray tube is usually poorer than at the center of the tube but the amount of defocusing can be decreased considerably by using balanced deflection.

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*A sweep-generator of interest developed at the David Taylor Model Basin provides a forward and reverse sweep which are displaced from each other on the vertical axis of the cathode-ray tube [36].

(iii) Beam brightening. The cathode-ray-tube beam is always extinguished when no sweep voltage is being generated, but when the sweep is tripped, the beam must come up to full and constant intensity in a time short compared to the duration of the sweep. Usually the beam is required to be extinguished at the end of the sweep, although, by using a large sweep deflection, the beam can be displaced off screen where it may not cause fogging of the film. This technique, however, occasionally leads to fogging from internal reflections of the beam inside the cathode-ray tube and has consequently not been used at UERL in equipment intended for use in air-blast investigations.

The simultaneous initiation of the beam brightening and the start of the sweep is straightforward, but the extinction of the beam at the instant the sweep has stopped is not as conveniently accomplished. In the most satisfactory beam-brightener circuit for sweep-generators that has been used in this laboratory, the sweep duration is determined by a circuit which controls the beam-brightener duration, so that automatic extinction is obtained. Another method of obtaining beam brightening for sweep-generators makes use of a circuit which differentiates the output of the sweep [25]. Since the sweep voltage varies linearly with time, its derivative is a constant proportional to the sweep speed during the course of the sweep but zero when the sweep output is at a fixed potential. By connecting a differentiating circuit to the sweep output a pulse is obtained, the magnitude of which is proportional to the sweep speed, that starts at the beginning of the sweep and stops at the end. Amplification is required, and if the output of the sweep is negative, phase inversion of the differentiated signal is also necessary. The output of the amplifiers must usually be passed through a limiter to eliminate 60 cps modulation and instability. Since the magnitude of the beam brightening pulse is required to increase with the sweep speed, it might be imagined that a differentiating type of beam-brightener circuit would provide automatic intensity control. Actually, however, the output of the differentiator circuit depends too much on the sweep speed, and more than one differentiating circuit (that is, the RC combination connected directly to the sweep output) is needed to cover a wide range of sweep speeds.

The amplitude of the brightening signal required at the cathode-ray-tube grid is about 30 to 60 v. The brightening will not be of constant intensity if condenser coupling is used between the beam-brightener stage and the cathode-ray-tube grid unless the time constant of the coupling circuit is 10 to 100 times the duration of the brightening pulse. Thus not only are very large time constants required in the coupling network, but repeated tripping of a beam-brightener with a long time constant coupling will cause the amplitude of the signal applied to the cathode-ray tube grid to decrease, and the intensity will fade. This is very inconvenient when adjusting the intensity and focus of the cathode-ray tube. Changes in the plate voltage of the beam-brightener stage or in the voltage at the cathode of the cathode-ray tube, whether due to either 60-cycle hum or line-voltage fluctuations, are transmitted to the cathode-ray-tube grid by virtue of the low AC impedance of the coupling condenser. Direct-coupled beam brightening is therefore desirable for brightening durations greater than about 50 msec.

(iv) Synchronization. A fairly long-duration positive pulse is used for tripping the sweep-generators used in this laboratory. It is essential that the tripping circuit in the sweep-generator be independent of spurious signals that might occur before or during the sweep, yet the circuit must not fail to trip on the correct pulse.

(b) Sweep-generator for use with the DuMont type 208 oscillograph. — The sweep-generator shown schematically in Fig. 11 is used with the DuMont type 208 oscillograph to provide a single linear sweep and beam brightening for durations ranging from 1.5 to 480 msec.

The circuit consists of a synchronizing pulse amplifier (T_1), a flip-flop circuit, that serves as a pulse sharpener (T_2 and T_3), a flip-flop circuit which generates the beam-brightener pulse and controls the duration of the sweep and brightening (T_4 and T_5), a phase inverter in the beam-brightening circuit (T_6), a switching tube (T_7), and a constant current tube (T_8) that generates the sweep. The flip-flop and trigger circuits are discussed in more detail in Appendix C.

The sweep is started when the second flip-flop circuit (T_4 and T_5) is tripped by a pulse from T_3. The firing of the second flip-flop circuit cuts off the switching tube T_7 and starts condenser C_2 charging through the constant current tube T_8, generating a negative linear wave at the plate of T_8, which is stopped when the grid bias on T_7 becomes low enough to start it conducting again. The plate of T_8 is connected to one of the horizontal deflection plates of the cathode-ray tube, the other horizontal plate being grounded, so that the deflection is unsymmetrical.

The brightening pulse is generated by the second flip-flop circuit. The duration of the brightening is determined by the time constant of the condenser coupling between the two stages of this circuit; switch S_3, the coarse duration selector, controls the size of condenser C_1; and switch S_4, the fine control, selects the value of resistance. The positive pulse from T_4 is not of sufficiently constant amplitude to provide uniform beam intensity so that the beam brightening pulse has to be obtained from the inverted output of T_5, which has a more rectangular wave shape (see Appendix C). The need for a phase inverter is eliminated in the beam-brightener circuit used in the Mobile Laboratory described in Sec. 6.5. A voltage swing of about 500 v is obtained to drive the resistance divider in the oscillograph that connects to the grid of the cathode-ray tube [see Sec. 7.3(c)].

When the second flip-flop circuit resets, turning off the beam, it also stops the sweep and the voltage at the plate of T_8 returns to its initial value. Thus the sweep and the beam brightening are stopped simultaneously. The duration t of the sweep is determined by the second flip-flop circuit but the charging rate, and consequently the voltage developed at the plate of T_8, is controlled by the value of the plate current in T_8

and the size of the charging condenser C_2. The voltage $\underline{V}$ developed at the output of the sweep in time $\underline{t}$ is given by

$$V = \frac{1}{C_2} \int_0^t i \, dt \qquad (6.1)$$

where $\underline{i}$ is the plate current in T_8. Since this tube operates approximately as a constant current device, $\underline{i}$ is constant and

$$V = \frac{it}{C_2} \qquad (6.2)$$

Thus, for a given value of $\underline{t}$ and C_2, the amplitude of the sweep is determined by $\underline{i}$, which is controlled by potentiometer R_3 in the cathode of T_8. The condensers C_2 are selected by S_3, the same switch which selects C_1. The values of C_2 corresponding to a certain size of C_1 are determined by the value necessary to give sufficient sweep amplitude (about 275 v) when the fine duration control S_4 is set for minimum duration. The fine duration control changes the duration of the sweep and beam brightening by a factor of about two so that the amplitude control must be able to change the current in T_8 by a factor of two. Although changes in the cathode resistance change the equivalent dynamic plate-resistance of the pentode, no effect has been observed on the linearity of the sweep. The sweep is probably linear to about 1 percent. The shield of T_8 must be connected to its cathode or to B- to eliminate 60 cps modulation of the sweep.

Positioning of the sweep is obtained by potentiometer R_2 which controls the untripped voltage on the plate of T_5 and thus the voltage of the sweep output.

The input circuit (T_1) delivers a tripping pulse to the sweep when a switch connection is made ("make circuit") or broken ("break circuit") across the input or when a 6-v pulse is applied to the input. It will operate properly when a tripper is connected to the sweep by as much as 1000 ft of microphone cable.

The duration of the pulse which trips the second flip-flop circuit must be short compared to the reset time of the flip-flop in order to make the reset time independent of the form of the tripping pulse. The first flip-flop circuit (T_2 and T_3) sharpens the pulse from the input amplifier (T_1) and also serves to isolate the sweep from the tripping circuit for the duration of the sweep. The first flip-flop circuit, which does not reset for about 500 msec, will not be affected, when it is in a tripped condition, by a second positive pulse from the input amplifier, and, although it is sensitive to large negative pulses, it will not respond to small negative signals.

An internal trip switch, S_5, is included to trip the sweep manually without an external circuit. This switch is connected directly to the second flip-flop circuit so that it is not necessary to wait 500 msec between the occurrence of successive sweeps.

Two relays are included in the circuit which are not shown in Fig. 11: one to turn the beams on continuously for setting the focus and intensity of the cathode-ray tube and for general testing, and one to provide an automatic change in the duration of the sweep. These are similar to the relays used in the beam-brightener for the Mobile Laboratory, which is described in Sec. 6.5.

The power supply shown on the circuit diagram is supplied with voltage-regulator tubes to eliminate line-voltage fluctuations, since these fluctuations are capable of tripping the circuit. If very erratic line voltages are encountered, an electronically-regulated supply might be necessary.

The sweep-generator and power supply are built on a 17X13X3 in. chassis with a standard 8-3/4 in. rack panel. All connections are made by plugs at the rear of the chassis.

Six of these sweep-generators have been in use for over two years and have given very satisfactory service. Two difficulties have been encountered: (1) The condensers C_1 and C_2, which are selected to within 2 percent of the nominal values before installation, tend to drift. Ordinary mica and paper condensers have been used, some of them of rather poor quality. On the average, one of the six sweep-generators requires a new condenser every 3 to 6 months. (2) The resistors which determine the bias in the flip-flop circuits tend to drift, causing the circuit to be either too sensitive or too insensitive to trip pulses, depending on the direction of the change in resistance. Ordinary IRC ½-w resistors have been used.

Although these sweep-generators have given satisfactory service, they are lacking in two desirable features: (1) Push-pull sweep deflection, which provides better focus than unsymmetrical deflection. (2) A continuous sweep that can be used without disconnecting the single sweep and which would be convenient for testing. A simpler and more satisfactory circuit of the same type could be designed using a flip-flop circuit based on Schmidt's trigger circuit [35] (see Appendix C).

(c) Sweep-generator used in the Mobile Laboratory. — Figure 12 is the schematic circuit of the sweep-generator used as a test unit in the Mobile Laboratory. It is based on a similar circuit developed by Cole for use in underwater shock-wave investigations [33]. This unit is somewhat more complicated than is really required for test purposes but its development was guided by a need for a new circuit which included certain features omitted in the sweep-generator described above. The circuit shown in Fig. 12 provides single and continuous linear sweeps with a repetition rate varying from 1 to 2000 cps; it has a push-pull output and includes provision for adjustment of the mean output potential.

The circuit consists of a trigger circuit, T_1 and T_2, a switching tube, T_3, a series charging tube, T_4, a cathode follower, T_5, push-pull output tubes, T_6 and T_7, and a synchronizing signal amplifier, T_8.

For single-sweep operation the switches marked 8A, 8B, and so forth, which are ganged together, are set in the center (1) position. The sweep is initiated by closing the internal trip microswitch S_2 or by an external positive signal of about 8 v applied to the external trip input. Either of these signals trips the flip-flop circuit, consisting of tubes T_1 and T_2, which cuts off T_3 and causes the sweep-generating condenser C_1 to discharge through T_4. The cathode follower T_5 follows the voltage on C_1 and applies the sweep signal to T_6 which, together with T_7, is a cathode-coupled push-pull amplifier which connects to the deflection plates of the cathode-ray tube. The sweep stops when the voltage across C_1 is low enough to start T_3 conducting. A short time after the sweep has stopped, the flip-flop circuit resets itself and the circuit is in its original condition.

Linearity is controlled by feedback through R_3 from the cathode of T_5 to the cathode of T_4. As the sweep progresses the voltage on the cathode of T_5 drops, reducing the current through the cathode circuit of T_4, which is compensated by an increase of plate current due to the change in grid bias, thus counteracting the exponential decay of the discharge current in C_1. The feedback is controlled by R_3; the sweep can be overcompensated or undercompensated by adjusting this control. Since the nonlinearities in the output-amplifier tubes and in the cathode-ray tube are probably greater than the nonlinearity in the sweep-generating circuit, the compensating network may be unnecessary. No linearity measurements have been made on this unit, but good linearity is obtained in the similar circuit used for underwater shock-wave studies.

The circuit operates continuously if the switches 8A, and so forth are in position (2). The flip-flop circuit is converted into a trigger circuit, with two stable operating conditions, controlled by the bias on T_1, which is proportional to the sweep voltage developed across potentiometer R_5 in the cathode of T_5. During the course of the sweep, T_1 is conducting; at the end of the sweep the trigger circuit is tripped and T_1 is cut off, the sweep flies back, the trigger circuit is reset, and the sweep starts again.

The sweep frequency is determined by the condensers C_1, which are selected by switch S_3, and by potentiometer R_4. Amplitude is controlled by potentiometer R_6, and potentiometer R_7 is adjusted to reduce the voltage across R_6 to zero when the circuit is connected for single-sweep operation, so that adjustment of R_6 does not change the positioning. The positioning is obtained from potentiometer R_{11}. Potentiometer R_8 controls the mean voltage on the output tubes and consequently controls the mean potential of the deflection plates with respect to the second anode of the cathode-ray tube. Potentiometer R_1 is adjusted to obtain equal amplitudes on single and continuous sweeps. Switch S_1 is used for line-frequency synchronization and potentiometer R_2 controls the amplitude of the synchronizing signal applied to the trigger circuit.

The complicated switching on switches 8A, and so forth, is required to provide semi-automatic operation in conjunction with the other equipment in the Mobile Laboratory (see Chap. 10 and 11). When a photograph is to be made with the rotating-drum cameras used for recording the pressure-time curves, this switch is set in position (0), which switches the horizontal deflection plates of all the cathode-ray tubes to the resistance divider which includes potentiometers R_9 and R_{10}. R_{10} then controls the position of the spot and R_9 controls the mean potential of the deflection plates. Switch 8A is in the master-control-pilot-light circuit [see Sec. 10.2(a)].

The sweep is operated from a regulated power supply which supplies +300 and -200 v. This power supply is called the "Master-Control-Power Supply" and is similar to the power supplies described in Sec. 11.3(a). It is constructed on a 17X13X3-in. chassis with a standard 7-in. rack panel. All connections are made to plugs on the back of the chassis and the circuit grounds are insulated from the chassis. The external synchronization signal can also be applied to jacks on the front of the panel.

No provision is included for beam brightening because this unit was not intended for photographic use. The flyback time of the circuit is longer than is desirable; this might be improved by replacing T_3 by a tube with lower dynamic plate resistance and by using smaller condensers in C_1 and larger current in T_4. The over-all high-frequency characteristics of the circuit are probably impaired by the large number of high-impedance resistance dividers and volume controls used. The linearity of the output amplifier, and in particular the effect of the mean potential control on its linearity, has not been investigated. The synchronization method on continuous sweep is not entirely satisfactory and the feedback control, R_5, is difficult to adjust because it changes the operating conditions of T_1 as well as the amplitude of the signal applied to T_1. Although the circuit does have these shortcomings, it has been quite stable and no servicing of the one unit built has been required in a year and a half of almost continuous operation.

6.5. Beam-brighteners

The basic considerations which govern the design of beam-brighteners are discussed in Sec. 6.4(a).

(a) Beam-brightener for use with the DuMont type 208 oscillograph. -- The beam-brightener shown schematically in Fig. 13 is used to provide beam brightening for the DuMont type 208 oscillograph when used with rotating-drum cameras. The beam brightening durations available are from 15 to 1000 μsec.

The circuit is almost identical to the first stages of the sweep-generator shown in Fig. 11. Two beam-brightener units are built in one 17X13X3-in. chassis and are operated from the single power supply shown. A decoupling condenser is inserted in the plate circuit of T_5 to prevent the two units from interacting with each other through the power supply.

A "beams-on" relay is shown in the figure. The function of this relay, as well as those of a "duration-change" relay which has recently been included and is not shown in the circuit diagram, are described in part (b) of this section.

(b) Beam-brightener for use in the Mobile Laboratory. — Figure 14 is the schematic circuit of the beam-brightener used in the Mobile Laboratory. Two identical units provide a brightening pulse ranging from 5 msec to 2.5 sec duration to the 12 cathode-ray tubes, eight of which are used for recording the pressure-time curve and four for timing calibration. The circuit of the cathode-ray tubes is described in Sec. 7.3(b) and the power supplies referred to in the following are described in Sec. 11.3(b).

The circuit is divided into two parts: The first section, which consists of a synchronizing pulse amplifier, T_1, and a flip-flop circuit, T_2 and T_3, that serves as a pulse sharpener, is operated from a 300-v regulated power supply (the Master-Control Power Supply) the negative side of which is grounded. The second section contains the stage which generates the beam-brightening pulse (T_4 and T_5) and is operated from a 300-v regulated power supply (the Beam-Brightener-Power Supply) the positive side of which is connected to the negative terminal of the high-voltage cathode-ray-tube power supply. The intensity control of each cathode-ray tube determines the cathode voltage of the tube, which is always equal to or more positive than the negative terminal of the high-voltage supply, and the beam-brightener determines the grid voltage. The grid is 90 v below the negative terminal of the cathode-ray tube supply when the beam-brightener is not tripped and is at the potential of the high-voltage terminal when the beam-brightener is tripped.

The operation of the first part of the beam-brightener, containing the synchronizing pulse amplifier and pulse sharpener, is similar to the operation of the equivalent stages in the sweep-generator shown in Fig. 11, although a different type of flip-flop circuit is used for the pulse sharpener. Two separate connections are provided for external synchronization pulses: pin 1 connects to the calibration-step generator [see Sec. 10.2(c)], and pin 2 to the circuit used for synchronizing with the detonation. Switch S_4, which is ganged to the beam-brightener-duration control S_1, provides two durations for the pulse-sharpener stage. These are provided to reduce the minimum time that is necessary between the application of successive tripping pulses when short beam-brightener durations are used. This is convenient for testing but does not affect the operation during recording.

The brightening pulse is obtained directly from the second flip-flop circuit (T_4 and T_5) without the use of a phase inverter. It was found that the output of the normally conducting tube (T_5) in this type of flip-flop circuit is sufficiently rectangular to provide relatively constant spot intensity for the entire duration of the brightening pulse. The output is taken from the midpoint of the load resistor of T_5 because the entire voltage swing is not required. The brightening duration is controlled by switches S_1 or S_2, depending on the position of relay RL-3, the "duration-change" relay, and by S_3. These switches determine the time constant of the resistance-capacity coupling network in the flip-flop circuit.

The three relays, RL-1, RL-2, and RL-3, are controlled by the master control. When relay RL-1, the "beams-on" relay, is energized, the cathode-ray-tube grids are connected to the beam-brightener in the normal manner, but when it is de-energized, as shown in the figure, the cathode-ray-tube grids are connected to the negative terminal of the high-voltage supply, which is the potential of the grids when the beam-brightener is tripped. Thus a steady intensity is obtained which is equal to the intensity during brightening. This relay is extremely useful for setting intensity and focus on the cathode-ray tubes and for general testing; the additional circuit complications are compensated for many times over by the increased efficiency and convenience of operation possible with the inclusion of the beams-on relay.

The sequence of recording in the Mobile Laboratory requires the use of the other two relays. The sequence is: (1) An amplitude-calibration step with a beam-brightening duration considerably shorter than one drum revolution. (2) A second calibration step with the same beam-brightening duration. (3) The shot record, including a simultaneous timing calibration, with a brightening pulse lasting for approximately one drum revolution. (4) An amplitude calibration step with a beam-brightening duration approximately equal to the time of one drum revolution. Short beam-brightening durations are used for the first two calibration steps to minimize the length of the traces on the film, because extra lines cause confusion in analyzing the records, and a long duration is used for the last calibration step to give an estimate of the over-all time constant of the equipment. Thus, on the channels employed to record the pressure-time curve, the duration of the beam brightening for the first two operations is different from the duration for the second two operations, and the beam of the cathode-ray tubes used for timing calibration is only brightened during the recording of the shot.

Relay RL-2, the timing relay, connects the grids of the cathode-ray tubes employed for timing calibration to the beam-brightener while the shot is being recorded and connects the grids to the negative side of the beam-brightener power supply (-1650 v) at all other times except when the beams are turned on by the beams-on relay.

Relay RL-3, the duration-change relay, changes the beam-brightener duration from a coarse duration selected by switch S_1, used for the last two operations in the sequence, to a coarse duration selected by switch S_2, which is used for the first two operations in the sequence.

The grids of all the cathode-ray tubes are permanently connected to the negative side of the beam-brightener power supply by 5-megohm resistors in order to eliminate slight flashes on the tube screen which occur when the relays are switched on and off. The relay coils are shunted by small resistors which reduce the inductive signal generated by the relays when they are de-energized, which, if it were not eliminated almost completely, would sometimes trip the beam-brightener.

Two beam-brightener units are built on a 17X13X3-in. chassis with a standard 7-in. rack panel. All connections, except the provision for a remote manual tripping switch, are made by plugs at the rear of the chassis. Double-pole double-throw relays are used, one pole for each beam-brightener unit. All the components in the second section of the beam-brightener circuit must have adequate insulation to withstand the high voltages to which they are subjected. The 6SL7 employed for T_1 is divided between the two beam-brightener units, one triode element being used in each unit.

The main difficulty with this circuit during its operation in the Mobile Laboratory was the failure of some of the wiring and relays because of inadequate insulation.

Chapter 7

CATHODE-RAY TUBES

A recording device for use in blast measurements must be capable of producing a permanent record of the transient electrical signal produced by the gauge. The considerations involved in the choice of a recording device are: (1) adequate sensitivity and stability; (2) accuracy of resolution; (3) ease with which the final record can be analyzed; (4) frequency response; and (5) convenience, simplicity, and ruggedness.

7.1. Comparison of recording devices

The devices most commonly used for recording blast waves are cathode-ray tubes and string galvanometers, although other devices may prove practical for the measurement of blast from extremely large charges.

The cathode-ray tube, although more cumbersome than other indicating devices, is used for the recording of short-duration transient phenomena because of its superior high-frequency characteristics, which are limited only by electron transit time. Since a cathode-ray tube responds to static changes in potential, it can also be used to record low-frequency phenomena. The cathode-ray tube is the only type of instrument used for recording blast waves at UERL.

Extremely compact and rugged galvanometer oscillographs of relatively high sensitivity are available, but the upper limit of their frequency response is from 2000 to 4000 cps. Galvanometers of this type are made by the Hathaway Instrument Company and the Heiland Research Corporation. This response is adequate for the measurement of the blast from large charges but is inadequate for recording the pressure waves from small charges.

Mechanical recorders such as the direct-inking oscillographs made by the Brush Development Company have a frequency response flat to 120 cps only. This is a higher response than most other types of mechanical recorders, but is insufficient for blast measurements on the charges usually investigated.

Magnetic wire recorders have not been considered at this laboratory.

7.2. Characteristics of cathode-ray tubes [35, 37]

(a) Sensitivity. — The deflection sensitivity of a high-vacuum cathode-ray tube of the electrostatic deflection type is defined as the deflection on the tube screen for a signal of unit potential difference applied to the deflection plates. The sensitivity varies inversely with the accelerating voltage and on intensifier-type tubes varies approximately with the inverse square root of the intensifier voltage, all voltages being referred to that of the cathode. The sensitivity also depends on the geometry of the tube, and in commercial tubes increases with the diameter of the screen.

The cathode-ray tubes used at UERL have all been of the intensifier type manufactured by the Allen B. DuMont Laboratories, Inc. Intensifier type tubes are used because, for equal spot intensities, they provide greater sensitivity than the ordinary tubes.

Since the sensitivity of a cathode-ray tube depends on the electrode voltages, it is essential, if the sensitivity of the recording system is to be stable, that these voltages be kept constant. At this laboratory it has been found advisable to use regulated power supplies for the accelerating potential and, in some cases, for the intensifier voltage as well.

(b) Linearity. -- A number of sources of nonlinearity occur in cathode-ray tubes and, although most of these distortions are corrected in properly designed tubes, two sources of nonlinearity introduce errors when the tubes are used for photographic recording.

(i) The photograph of a single sweep along the horizontal axis of the tube when no signal is applied to the vertical axis should appear on the photograph as a straight line, but it often appears curved. Furthermore, the photograph of the envelope of a sinusoidal signal on a single sweep sometimes appears barrel-shaped.

(ii) Nonlinearity is introduced when a tube with a curved screen is photographed [35]. The nonlinearity results from the fact that the photograph on a plane film of a uniform scale on a curved surface appears compressed at points not on the principal axis of the lens. For example, if a type 5CP series tube is photographed by a lens 24 in. from the front of the screen this distortion will be greater than 1 percent for centered deflections of 2 in. (that is, a deflection from 1 in. below the center of the screen to 1 in. above). The error increases with the amount of the deflection and, to a less marked degree, decreases with increasing distance between the lens and the screen.

An additional nonlinear distortion, which is indirectly due to the cathode-ray tube, may be introduced by the amplifiers because of the very large signals required for the deflection of the spot.

(c) Intensity. -- The high writing speeds necessary for the photography of transients require high cathode-ray-tube spot intensities and sensitive photographic equipment. The peak region of the pressure-time curves is the most difficult to photograph, particularly when the pressure-time curve is irregular and of short duration, as on measurements of blast at high pressures or from small charges. Since the effective writing speed of the tube increases approximately with the square of the accelerating voltage on the tube [37], high accelerating voltages are required for high-speed recording. Thus a compromise must be made between the use of high accelerating voltages and the need for maximum sensitivity. The effect of the photographic equipment in determining the writing speed is described in Chap. 8.

A detailed study of the optimum accelerating voltages for different conditions has not been made at this laboratory, but it has been found that an accelerating voltage of approximately 1350 v and an intensifier potential of 2550 v on a type 5CP11 tube gives adequate intensity to record pressure-time curves with an initial decay-time of about 0.2 msec. These photographs were made on Fluorographic film, with an F/2, 5 cm lens 26 in. from the screen, on a rotating-drum camera running at a film speed of 3.2 msec/in. The deflection on the screen was 2 in. and the magnification was about 0.08. Somewhat faster writing speeds can be obtained under the same conditions by special selection of the cathode-ray tubes, but this is a difficult and costly procedure.

(d) Focus. — The focus of a cathode-ray tube is extremely important because it governs the precision with which a deflection of the trace can be measured. If it were possible to develop a cathode-ray tube with sharper focus than can be obtained usually, the recording equipment could be improved in one of three ways: (1) the minimum deflection required could be decreased without causing a loss of accuracy, thus increasing the over-all sensitivity of the recording equipment; (2) smaller cathode-ray tubes (which are less sensitive than large tubes) could be used, providing a more compact unit; or (3) the accuracy of measurement could be improved.

The focus of a cathode-ray tube is affected by the potentials of the deflection plates and to obtain optimum focus the mean potential of the deflection plates must be approximately the same as the potential of the second (accelerating) anode. If the mean potential is not properly adjusted, the cathode-ray tube spot will be roughly elliptical rather than circular, and the major axis of the ellipse will be larger than the radius of the circle obtained under optimum conditions. The ellipticity of the spot causes a difference in spot width along the two axes of the tube, and is equivalent to optical astigmatism. Variations in the geometrical alignment of the tube may cause slight astigmatism which can be reduced by making small adjustments in the mean potential [35].

Defocusing of the trace occurs near the edges of the screen, but can be reduced by using symmetrical, that is, push-pull, deflection. Unsymmetrical deflection can cause astigmatism as well as defocusing.

Defocusing may also occur when the control grid is driven positive, which may take place during beam brightening.

(e) Screen materials. — A number of different types of cathode-ray tube screens are available. The choice of a suitable screen phosphor for photographic recording is governed by its spectral characteristics, its persistence, and the screen efficiency (usually expressed as ft lamberts/μa). Moving-film cameras require short-persistence screens to prevent blurring of the image on the film.

The screen phosphors usually used for photographic recording are the P5 and the P11. Some confusion has existed in the past in regard to P5 screens, which were made with either a blue sulphide short-persistence screen or a calcium tungstate very-short-persistence screen. The blue sulphide screen is now designated P11 and the calcium tungstate screen is now designated P5 [37]. All tubes used at UERL for studying shock waves in both air and water have been of the blue sulphide type. The P11 screen has a sufficiently short persistence for most purposes, has a higher screen efficiency than the P5, and has a spectral characteristic quite similar to the latter.

Long-persistence green screens, such as the P2, might be expected to be more satisfactory for photographic recording with fixed-film cameras than the short-persistence screens, but their spectral characteristics are not as suitable for photographic recording as the P11 screen. In general, despite their longer persistence, the green-screen tubes are not recommended for photographic purposes [38, 39].

(f) Spurious signals. -- The most troublesome source of spurious signals in a cathode-ray tube is magnetic pickup from power transformers. This pickup can be best eliminated by removing all transformers and high-current lines from the vicinity of the cathode-ray tube. Magnetic shields, such as the mu-metal shields made by the Metallic Arts Company, are usually placed around the tube but they are not completely effective in removing all pickup when transformers are located near the tube.

Electrostatic fields in the neighborhood of the cathode-ray tube are capable of giving rise to a spurious signal. These signals are not usually troublesome, however, because the magnetic shield eliminates them almost completely.

Occasionally an electrostatic charge accumulates on the tube screen and causes spurious deflection of the trace. Moistening the tube face and cleaning will help reduce this distortion.

Intensity modulation of the trace at power-line frequency is introduced if the plate supply is improperly filtered, particularly if the beam-brightening pulse is condenser coupled to a low-voltage source.

7.3. Cathode-ray tube circuits

(a) General considerations. -- The cathode-ray-tube circuits used at this laboratory are for the most part conventional. The main electronic features included in the circuits designed for the recording of air-blast pressures at UERL which are not generally incorporated in cathode-ray-tube circuits are: (1) regulated high-voltage supplies; (2) provision for beam-brightening; (3) inclusion of a potentiometer to control the voltage of the second anode of the cathode-ray tube; (4) careful isolation from the tubes of sources of magnetic fields.

The mechanical mounting of the tube which is used at UERL is somewhat unconventional: the tube mounting can be moved lengthwise, in order to adjust the screen-to-lens distance for variations in tube length, and the screen or a calcium tungstate very-short-persistence screen. The blue sulphide screen is now designated P11 and the calcium tungstate screen is now designated P5 [37]. All tubes used at UERL for studying shock waves in both air and water have been of the blue sulphide type. The P11 screen has a sufficiently short persistence for most purposes, has a higher screen efficiency than the P5, and has a spectral characteristic quite similar to the latter.

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The mechanical mounting of the tube which is used at UERL is somewhat unconventional: the tube mounting can be moved lengthwise, in order to adjust the screen-to-lens distance for variations in tube length, and the tube sockets can be rotated and securely fixed at any orientation to enable the deflection plates to be lined up with the axis of rotation of drum-type cameras. A movable felt-lined flange is provided at the face of the tube to hold it solidly in place and to prevent light from leaking around the edges of the screen.

It is probably not advantageous to use cathode-ray tubes with screens larger than 5 in. screen diameter, and tubes smaller than 3 in. screen diameter are not, at present, supplied with P11 screens. Five-in. tubes have been used in air-blast equipment for recording the pressure signal primarily because they are more sensitive than 3-in. tubes. For purely mechanical reasons the new type cathode-ray tubes which have 12 pin di-heptal bases and snap-type intensifier connections, such as tubes of the 5CP series, are preferred to the older type tubes which have medium magnal bases and grid-cap intensifier terminals.

(b) Cathode-ray tube circuit in the Mobile Laboratory. -- The Mobile Laboratory contains 12 cathode-ray tubes of which eight are type 5CP11 and four are type 3FP11. A pair of 5-in. tubes, each of which is connected to its amplifier and which record the gauge signals, and one 3-in. tube, which is used to provide a timing calibration applied simultaneously with the recording of the pressure wave, are photographed by one drum of a rotating-drum camera. Four of the 5-in. tubes and two of the 3-in. tubes, termed Bank 1, are photographed by two drums of the rotating-drum camera and are connected to one beam-brightener. The other six tubes, termed Bank 2, are arranged in a similar manner. The two drums which photograph the tubes in Bank 1 rotate at the same speed, but their speed is independent of that of the two drums which photograph the tubes in Bank 2. The arrangement of the cathode-ray tubes is shown in Fig. 39, Chap. 12.

The schematic circuit of the cathode-ray tubes in Bank 1, which is identical to Bank 2, is shown in Fig. 15. Only one of the four 5-in. cathode-ray tubes and one of the 3-in. tubes in Bank 1 are shown, but connections to the other tubes are similar.

Both banks are supplied by one high-voltage regulated power supply [see Sec. 11.3(b)] and all the tube heaters are connected in parallel to a 10-amp transformer, the center tap of which is connected to the negative terminal of the high-voltage supply. One resistance divider is connected across the supply to provide the electrode voltages for the 5-in. tubes of Bank 1 and another divider is used for the 3-in. tubes. Separate potentiometers are included for each tube to control the intensity and focus, and the potential of the second (accelerating) anode. (The values of these potentiometers are not well chosen. The sizes used were governed by the available supply when this unit was constructed.)

The deflection plates D_3 and D_4 of each 5-in. tube are connected to an amplifier and the same plates of the 3-in. tubes are connected to the output of the timing unit [see Sec. 9.3(c)]. The deflection plates D_1 and D_2 of all tubes are connected to the sweep-generator [see Sec. 6.4(c)]. The control grids of all the 5-in. tubes in Bank 1 are attached to the output of one beam-brightener and the grids of the two timing tubes are connected to the same beam-brightener through the timing relay [see Sec. 6.5(b)]. The control grids of Bank 2 are connected to another beam-brightener unit.

When the beam-brightener is not in the tripped condition, the control grids of the cathode-ray tubes are held at 90 v below the negative terminal of the high-voltage supply. When the beam-brightener is tripped, or the beams-on relay [see Sec. 6.5(b)] actuated, the grids are at the same potential as the negative high-voltage terminal and the spot intensity is determined by the intensity control connected to the cathode of each cathode-ray tube.

When the cathode-ray tubes are photographed, the sweep-generating stages of the sweep-generator are disconnected. They are replaced by a circuit in the sweep-generator [see Sec. 6.4(c)] which controls the spot position and adjusts the mean potential of the deflection plates. Adjusting the horizontal position of the spot from time to time prevents screen burning.

The procedure for eliminating the ellipticity of the cathode-ray-tube spot on the 5-in. tubes, which is owing to astigmatism, is first to adjust the potential of the $D_1 - D_2$ deflection plates, by means of the control in the sweep-generator, to a value close to the mean output voltage of all the amplifiers. The voltage of the second anode is then adjusted on each individual tube to obtain minimum ellipticity. The mean potential of all the 3-in. tubes is then adjusted by the control in the timing unit and then the second anode of each timing tube is set. None of these adjustments are critical but they provide sufficient control to eliminate most of the astigmatism.

The cathode-ray tubes are mounted in rack panels in a standard relay rack as shown in Fig. 39. The tube sockets are mounted in brass brackets which slide on a bakelite base supported from the front panels. Felt-lined flanges, which slide in brass tubes screwed to the panel, provide support for the front of the cathode-ray tubes and also serve as a light seal to prevent light in the cathode-ray tube housing from reaching the camera lenses. This housing is made of 20-gauge galvanized iron and completely surrounds all the tubes and wiring; it is the only electrical or magnetic shielding provided, but is completely adequate. The intensity and focus controls and the second anode adjustment are mounted on a bakelite panel to the left of the tubes, as shown in Fig. 39.

(c) Cathode-ray-tube circuit of the DuMont type 208 oscillograph. — The modified cathode-ray tube and power-supply circuit of the DuMont type 208 oscillograph is shown schematically in Fig. 16. The essential modifications to the cathode-ray tube circuit are: (1) provision for an increased intensifier voltage; (2) inclusion of a resistance divider for connecting direct-coupled beam brightening to the cathode-ray tube control grid.

The intensifier voltage is raised from the original value of +280 v to about +1150 v by including a half-wave voltage doubler (T_{19}) which is connected across the high-voltage winding of the power transformer and is provided with a simple filter. This circuit was originally developed at the David Taylor Model Basin. A 6.3-v filament transformer is added to supply heater power to T_{19}, and is so connected that the oscillograph can no longer be operated from a 230-v power line. The filter condenser in the voltage doubler is connected to the +280-v supply voltage to reduce the voltage across the condenser.

Inasmuch as the power supply from which the cathode-ray tube is operated is not regulated, the sensitivity of the oscillograph depends on line voltage. The effect of the unregulated supplies is to make it essential to use an extremely steady source of line voltage for operating the oscillograph (see Chap. 11).

Referring to Fig. 16, it is seen that the beam-brightening pulse [see Sec. 6.4(b)] is inserted at the phone jack labelled J_2. This is connected to the cathode-ray-tube control grid through a resistance divider which terminates at the negative terminal of the high-voltage supply. The resistance between the control grid and the high-voltage supply has been changed from 100,000 ohms to 400,000 ohms to decrease the attenuation in the voltage divider. The voltage divider in the modified circuit tends to make the grid more positive than in the original circuit. This change of voltage has been compensated by inserting a 50,000-ohm resistor between the intensity control and the negative terminal of the high-voltage supply and the resistor between the intensity control and the focus control has been lowered from 200,000 ohms to 150,000 ohms.

The rear terminal board of the oscillograph has been rewired with banana jacks and plugs so that either the vertical or horizontal amplifier can be connected to either pair of deflection plates of the cathode-ray tube. When a single-sweep generator is used, the horizontal amplifier is disconnected from the cathode-ray tube and connected to two banana jacks on the output of this amplifier. The sweep-generator is plugged into banana jacks connected to the horizontal deflection plates, which are spaced to receive a General Radio Type 274-M plug. The rear terminal board also contains two phono jacks, one for the beam-brightening connection and one for the spot-displacement connection. [See also Sec. 5.3(b)]

Chapter 8

THE PHOTOGRAPHY OF CATHODE-RAY TUBES

A description of the cameras, films, and photographic processes used to photograph cathode-ray tubes is presented in this chapter. Two kinds of cameras are employed in air-blast equipment at this laboratory: one type uses film attached to a rotating drum and the other uses fixed film. These two types of cameras are described in this chapter. Their relative advantages have already been compared in Sec. 6.2.

8.1. Factors which affect the photographic writing speed

The writing speed of a cathode-ray tube is the speed with which the cathode-ray-tube spot is moved. The maximum writing speed is the greatest speed with which the spot can move without producing a photographic image of insufficient intensity to be measurable; obviously the writing speed of a transient signal of a given rate of decay can be made smaller by reducing the amplitude of the deflection on the cathode-ray tube. For a given signal amplitude on the tube the writing speed that can be obtained in the photography of high-speed transients is determined by: (1) the intensity and spectral characteristics of the cathode-ray tube trace; (2) the lens aperture; (3) the speed and spectral sensitivity of the film; (4) the magnification in the optical system.

(a) Cathode-ray tubes. — The characteristics of cathode-ray tubes have been discussed in Chap. 7. It was pointed out in that chapter that, to increase the maximum beam intensity, it is necessary to reduce the deflection sensitivity of the cathode-ray tube.

(b) Lenses. — By using large lens apertures, the photographic writing speed may be increased without affecting the sensitivity of the recording system. Although the lenses used at UERL have an aperture of F/2, larger apertures would be desirable. The lens should be corrected for the usual aberrations, although chromatic aberration is probably of no particular importance in the photography of cathode-ray tubes.

(c) Film characteristics. — Obviously the higher the film speed (in the spectral region corresponding to the frequency of the light emitted by the cathode-ray tube) the greater the maximum writing speed of the recording system. The films which have been used at UERL are described in Sec. 5 of this chapter.

Photographic recording papers can be used when the required writing speed is low or when the accelerating voltages are high [15, 39, 40, 41], but these papers have not been employed at this laboratory.

The resolving power of the film may be a limiting factor in the accuracy with which records can be measured, although this has not been the case in cameras designed at UERL. Difficulty from this source is encountered when a very small image size is used, as, for example, when a large field of view is recorded on a small film.

(d) Effect of magnification. — The writing speed on a fixed film increases with a decrease in the magnification (magnification being the ratio of the image size to object size). An equation relating the intensity of the image to the magnification for a fixed object size is obtained as follows [42]: The intensity of the light striking the lens is inversely proportional to the square of the distance r from the lens to the source, and, therefore, the image intensity is inversely proportional to r^2. The image intensity is also inversely proportional to its area, and is thus inversely proportional to the square of the linear magnification M. The image intensity I_1, corresponding to a magnification M_1 and a lens-to-source distance r_1 is therefore related to the image intensity I_2, corresponding to a magnification M_2 and a lens-to-source distance r_2, by the equation

$$\frac{I_1}{I_2} = \frac{M_2^2\, r_2^2}{M_1^2\, r_1^2} \qquad (8.1)$$

The lens-to-source distance r is given by

$$r = \frac{f}{m}(1 + M), \qquad (8.2)$$

where f is the focal length of the lens, so that Eq. (8.1) becomes

$$\frac{I_1}{I_2} = \left(\frac{1 + M_2}{1 + M_1}\right)^2 \qquad (8.3)$$

For example, if $M_1 = 0.085$ and $M_2 = 0.2$ (the magnifications of the different types of UERL cameras), $I_1 = 1.22 I_2$, and thus an increase of intensity of about 22 percent is obtained by this decrease in the magnification.

The writing speed which can be obtained, however, with a camera in which the film moves uniformly (as distinguished from a motion-picture camera in which the film is not moving during the instant that a frame is being exposed), decreases with a decrease in the magnification. Consider a line source which is parallel to the axis about which the film is moving; its image on a uniformly moving film will be a broad band. Although the width of this band is determined by the magnification of the optical system, its length is not, and is determined only by the film velocity and the duration of the exposure. Thus the image intensity is inversely proportional to M instead of M^2. For a moving film, then, Eq. (8.3) becomes

$$\frac{I_1}{I_2} = \frac{M_1}{M_2}\left(\frac{1 + M_2}{1 + M_1}\right)^2 \qquad (8.4)$$

For example, if $M_1 = 0.085$ and $M_2 = 0.2$, $I_1/I_2 = 0.52$, or in other words the intensity is reduced by 48 percent when the magnification is decreased from 0.2 to 0.085.

8.2. General characteristics of UERL cameras

(a) Lenses. -- Leitz Summar F/2, 5-cm lenses with focusing mounts are used in the cameras constructed at this laboratory. The cameras are designed, wherever possible, to permit ready access to the lens so that it can be focused at the same time an image is observed on a ground-glass screen (or similar focusing device).

(b) Light-tight hoods. -- Light-tight hoods or compartments are provided to keep out stray light between the lens and the cathode-ray-tube screen. These hoods are used to avoid the necessity of darkening the entire operating room, a procedure which is frequently inconvenient. The hoods can be swung out of the way, permitting the cathode-ray-tube screens to be observed as though no camera were present. This feature has proven to be extremely valuable for the general operation of the equipment, as well as for testing, and at this laboratory it is considered that an arrangement of this type should always be included in an oscillograph camera.

(c) Shutters. -- Camera shutters are not required to provide accurate timing of exposure when cathode-ray-tube beam brightening is used, and in some types of cameras, such as the cut-film camera described in the following, a truly light-tight shutter is unnecessary. The shutters used at this laboratory are simple flaps or slides which are connected directly to a handle. This handle not only operates the shutter but also indicates clearly if the shutter is opened or closed.

Iris-type shutters have not been used on oscillograph cameras for air-blast measurements at this laboratory because: (1) they have a tendency to jam and stick in cold weather; (2) nothing external to the shutter indicates distinctively and unambiguously whether or not it is open; (3) they usually contain provisions for more than one type of shutter exposure so that the shutter can be improperly set; and (4) the mechanical complexity of commercial shutters makes them difficult to repair under field conditions. Focal-plane shutters offer no advantage over iris-type shutters for time or bulb operation.

(d) Viewing devices. -- All the UERL cameras are provided with a viewing device through which the trace can be observed while the recording is being made.

8.3. Fixed-film cameras

The fixed-film cameras employed for photographing the cathode-ray tubes in equipment for measuring air-blast pressures consist of a simple support and light-tight hood to which is fastened a lens and cut-film plate holder. Four exposures are obtained on one 6.5X9 cm film. Fixed-film cameras using 35 mm film have been employed by the Stanolind Oil and Gas Company [19, 20] by Princeton University [43], by the David Taylor Model Basin, and, in equipment intended for the study of underwater shock waves, by UERL [33]. Line drawings of a recent model of a cut-film camera for use with the DuMont type 208 oscillograph are shown in Fig. 17.

Referring to Fig. 17, the light-tight tube T, which supports the lens and plate holder, is attached to the case of the oscillograph with wing nuts W. This tube is attached to the mounting bracket M by a hinge HI which permits the entire camera to be swung up out of the way to enable the screen of the cathode-ray tube to be observed directly.

The lens (Leitz Summar F/2, 5 cm) is mounted on a formica block hinged to the light-tight tube, and the plate holder (Eastman Kodak 6.5 X 9 cm, metal) slides into the removable back, B. This back fits into the formica block in any one of four orientations. The formica block containing the lens and plate holder can be opened outwards to make the lens readily accessible for focusing and to enable the cathode-ray-tube screen to be viewed while shaded from direct light by the light-tight tube. The lens is located at one corner of the plate holder so that by rotating the removable back B four different exposures can be obtained on one film.

The shutter S is a simple flap of metal which is held against the lens by a coil spring attached to the shutter handle SH. The face of the shutter touching the lens is covered by felt. The end of the shutter handle is bent horizontally and can be ganged to the shutters of cameras on other oscillographs by attaching the handle of each camera to a rod running between the different cameras.

While a picture is being taken, the screen is viewed through the tube V and lucite prism P. Double-reflection in ordinary mirrors makes them an unsatisfactory substitute for the prism, and, although front-surfaced mirrors can be used, they are not as durable as prisms. Glass prisms however are preferable to lucite prisms.

All surfaces of the light-tight part of the camera which are not permanently fastened together are covered with felt, and the inside of the camera is painted flat black.

A ground-glass back from a Kodak "Recomar 18" camera is used for focusing the oscillograph cameras.

8.4. Moving-film cameras

The moving-film cameras used at UERL in equipment for the measurement of air blast have all been of the rotating-drum type. Rotating-drum cameras of slightly different design from those described in the following are used by the Stanolind Oil and Gas Company [21] and in equipment at UERL intended for the study of underwater explosions [33]. The General Radio type 651-AE oscillograph recorder, which is a camera with continuously-moving film, has been used by Princeton University [34], by the Ballistic Research Laboratory and, occasionally, in the measurement of underwater shock waves at UERL.

(a) General characteristics of rotating-drum cameras. — The two types of rotating-drum cameras used at UERL for the measurement of air-blast are essentially of the same design. A discussion of the basic considerations relating to this type of camera is presented here, and is followed by a description of the constructional details of the two kinds of cameras used.

(i) Drums. The film drums use approximately 10 in. of 35-mm film. Figure 19 includes a photograph of some typical drums and a line drawing of an older type of drum is included in Fig. 21. The film is fastened to the drum by one pair of fixed pins (FH in Fig. 21) and one pair of movable catches (M in Fig. 21). Tension is provided by the springs on the movable catches. Since it has been found that weather conditions affect the film length, these catches have to be carefully spaced to insure that they will hold properly films which differ slightly in length. A small strip of lucite about 1/32 in. thick, held to the drum by the movable clamps FC in Fig. 21, is used to clamp the ends of the film tightly against the drum.

The drums are made of aluminum and are hollowed out as much as possible to decrease their weight. The newer type drums shown in Fig. 19 are fastened to ½-in. shafts by a spring catch on the drum, which fits into a groove on the shaft, and by a keyed stop on the shaft. This arrangement allows the drums to be easily removed from the shaft to facilitate attaching the film to the drums. The spring catch can be seen on the top of the two upper drums in Fig. 19 and the keyed stop can be seen on the drum in the lower right-hand corner of this figure. The slot in the drum which fits this key can be seen on the drum resting on the bottom of the camera. The spring catch is released by pulling out the two small metal rods which serve as pins to fit into the groove on the shaft. The newer drums are provided with a flange on the outside edges to guide the film while the drum is being loaded. These two features, the flanges and the removable drums, greatly facilitate the process of attaching film to the drums.

The newer type drum has proved quite satisfactory from the point of view of loading and general operation. It is subject to one serious shortcoming, however: the trace cannot be accurately measured when it crosses the lucite strip used for holding down the ends of the film. The existence of a blind spot of this sort is, of course, an inherent characteristic of drum cameras, but the length of the blind spot on this type of drum is somewhat larger than that which can be attained by employing other kinds of film catches. An improved method of attaching the film to the drum, which was developed by the Stanolind Oil and Gas Company, uses a film whose ends are cut at an angle of about 45 deg and a drum with only two catches, one for each end of the film. By proper design of these catches the film can be made to lie reasonably flat over the entire drum. The films used on the Stanolind drums are 15 in. long and are overlapped for about ½ in. at each end. Although the focus across the overlap is not as good as on other portions of the film, it is considerably better than the focus under the lucite on UERL cameras, and on the Stanolind camera it is possible to measure a trace which appears across the overlap with almost as great an accuracy as on the uninterrupted portion of film. If the peak of the pressure-time curve were to occur on the actual joint between the ends, however, it would not be possible, even with the better film catches, to measure the peak with any degree of accuracy.

(ii) Film loading. Unlike moving-film cameras which use a continuous length of film, rotating-drum cameras are not well adapted to simple devices for daylight loading. In a permanent arrangement of equipment, whether mobile or stationary, the part of the camera containing the drum may be included in a darkroom which can be used for loading and developing. This is done in both units of UERL equipment and is a great convenience. The rotating-drum cameras employed for the measurement of underwater shock waves at this laboratory can be readily detached from the lens and taken to a darkroom for loading [33]. When the cameras used with the DuMont type 208 oscillograph, which are described in the following, are required for portable operation, they are provided with a cloth changing bag or light-tight wooden box that fits over the camera and which makes it possible to load the cameras in daylight without the use of a darkroom. Although this arrangement is adequate, it is not as convenient as an arrangement in which the camera is built into a darkroom.

(iii) Camera drives. The driving unit for a rotating-drum camera is required to be stable and must drive the drum at uniform but adjustable speeds. The requirement of stability is somewhat lessened by the use of a timing calibration at the same time the oscillogram is recorded, but in any case it is necessary that the drum speed be constant within about 10 percent in order to permit pre-setting of the speed with reasonable accuracy. The ordinary AC induction motors used at UERL have satisfactory stability when operated from a reasonably stable source of voltage.

Different speeds can be obtained either mechanically or electrically. Mechanical speed control by means of gears or pulley ratios is not the most desirable because these methods do not provide continuously variable speed. Gear systems have to be chatter-free if uniform drum rotation is to be assured. Continuously variable mechanical speed controls such as those supplied by Graham Transmissions, Inc., or by the Gaertner Scientific Company, are available, but they are quite expensive, and in limited use a unit made by Gaertner did not prove to be sufficiently stable or rugged. Electrical speed control over a wide speed range has not, for the most part, been recommended by motor manufacturers.

Pulley-cone combinations have been used for speed control at this laboratory and, although they are not entirely satisfactory, a more suitable method of speed control has not been found. Self-synchronous motors driven from a central continuously-variable-speed motor would provide a much more versatile system; however, no motors of the type directly suited to this application could be obtained at this laboratory during the war because of procurement difficulties. It is hoped that some such system may be devised when production of motors returns to normal.

As was pointed out in Chap. 6, it is desirable to synchronize with the explosion the position of the blind spot on the film in a rotating-drum camera. The only really adequate way of obtaining synchronization requires that the position of all the camera drums in one set of equipment be fixed with respect to one another, which implies that either a mechanical linkage between drums or an electrical linkage of the self-synchronous type be used.

Although direct linkage is required, the versatility of the recording equipment is severely restricted unless the relative speeds of different drums can be varied. Synchronization can be obtained when drums are operated at different speeds by adjusting the speeds of the fast drums to be integral multiples of the speed of the slowest drum.

The direct mechanical linkage of a number of drums is frequently prevented by the physical location of the cameras and by the difficulty of aligning a long shaft. The use of flexible shafting is not generally satisfactory because of the presence of considerable vibration, which modulates the speed of the drum. At certain speeds, however, this vibration may not be troublesome. Arrangements involving self-synchronous (selsyn) motors may prove to be invaluable for this application. The characteristics of this type of motor are being investigated at the time of writing.

(iv) Simultaneous timing. Rotating-drum cameras are well adapted for use with a timing calibration applied at the same time the oscillogram is recorded. Simultaneous timing requires the use of a light source, modulated at a known frequency, which can be photographed by the moving film for the duration of the phenomena being recorded.

Either a cathode-ray tube or a gas-discharge tube can be employed as a light source at the speeds ordinarily of interest for air-blast measurements. The use of a cathode-ray tube in this application is straightforward: the timing wave (oscillator signal) is applied to one set of deflection plates of a short-persistence cathode-ray tube and the beam intensity is controlled by the same beam-brightener which controls the cathode-ray tubes used to record the pressure-time curve. The cathode-ray-tube beam can also be modulated directly by the oscillator, but this necessitates the use of a circuit for mixing the oscillator signal and the beam-brightener signal. The main advantage of cathode-ray tubes for use as a source of light for timing calibrations is their ability to record as high a frequency signal as is recorded by the cathode-ray tubes used for the primary signal under observation. A practical but not fundamental advantage, which existed at the time most of the equipment employed at this laboratory was designed, was that they could be used without the need for any further development. The disadvantage of cathode-ray tubes is that they are bulky, as a 3-in. tube is the smallest size now available with a short-persistence screen.

Of the many kinds of gas-discharge tubes available, only three have been tested at this laboratory: strobotrons (such as the Sylvania 1D21/631-P1), neon lamps (such as the General Electric NE-45, ¼-w), and modulator glow (crater) lamps (Sylvania 1B59/R1130B). Of these, the neon lamps and the crater lamps have seemed to be the most practical. A circuit using a neon lamp is employed for the timing of a high-speed motion-picture camera [see Sec. 9.3(c)], but these lamps have not been found satisfactory for oscillograph photography, partly because they do not photograph well on Fluorographic film. A circuit for use with a crater lamp is described in Sec. 9.3(c), and a mounting for a crater lamp is shown as TT in Fig. 20. The crater lamps have been photographed with timing signals at frequencies from 100 to 10,000 cps. The main advantage of these lamps is their small size; their greatest disadvantage is the complexity of the circuit necessary to mix the beam-brightener and timing signals.

(v) Focusing. Unless the focusing of a rotating-drum camera is to be done by trial and error, which involves taking photographs at a great number of lens settings, a special focusing device is required. Two techniques for focusing these cameras have been employed at this laboratory: (1) A focus is obtained by viewing with a dental mirror the image on a film attached to the drum. This technique could be improved by constructing a mirror which could be attached to the drum, by providing magnification of the image, including a means of viewing the mirror easily, and by using a good diffusing screen which would have the same thickness as the film and which could be attached to the drum in place of the film. (2) A focusing drum, to be used in place of the regular film drum, was made out of lucite. The distance between the lens and the focusing screen (Eastman "Kodatrace" drawing material) attached to the lucite drum was adjusted to be the same as the distance between the lens and the film on an ordinary drum. Part of the lucite served as a prism to enable the image to be viewed at one side of the drum shaft. This device was not very satisfactory because too much light intensity was lost in the lucite and because the Kodatrace was not a good substitute for a ground glass. A focusing drum in which the lucite was replaced by glass with a ground surface would probably be very useful.

(b) Rotating-drum camera in the Mobile Laboratory. -- A rotating-drum camera containing four drums of the type described above is used for photographing the twelve cathode-ray tubes used in the Mobile Laboratory. Eight of these tubes, which have 5-in. screens, are used for the recording of the pressure-time curves and four, which have 3-in. screens, are used to provide a simultaneous timing calibration on each of the four drums. The camera is placed vertically and at right angles to the cathode-ray tubes, as can be seen by referring to Fig. 18, where the tubes are on the left and the four lenses can be seen in the background. The image of the cathode-ray tubes is reflected onto the camera lens by means of two front-surfaced mirrors (made by the Evaporated Metal Films Corporation) attached to the hinged door as shown in the figure. The camera itself is located in the darkroom of the Mobile Laboratory (see Fig. 38).

The arrangement of the four drums is shown in Fig. 19. One drum photographs two of the tubes used for recording the pressure-time curve and one of the tubes used to provide the timing calibration. These drums are described in part (a) of this section. The drums are belt driven by a 1/8-hp induction motor attached to a sheave on the central shaft at a point below the camera (not visible in the figure) and speed control is obtained by varying the pulley ratio between the motor and the central shaft and between each of the drum shafts and the central shaft. Thus the drum speeds can be varied in pairs only. The ratios of the steps on the pulley-cones inside the camera are two to one.

The lenses (Leitz Summar F/2, 5 cm) are mounted in brass plates attached to horizontal tie pieces which support the entire camera. The lens mounting plates are visible in Fig. 19 and part of the back of the lens used for the lower left-hand drum can just be seen. The pillow blocks supporting the shafts are also mounted on these tie pieces. The two tie pieces are attached to a ½-in. thick brass plate, shown in the background of Fig. 19, which also supports a pillow block below the camera which serves as a support for the central shaft.

The camera housing is made of bakelite and is hung from the two tie pieces, which fasten to a standard relay rack. The back of the camera consists of three hinged bakelite pieces. The central section of the back is attached to the camera by four studs, which can be seen in Fig. 19 extending from the edges of the camera sides. The top and bottom pieces of the back are fastened by clamps, the bottom pair of which can be seen in the figure, just below the bakelite housing. The two outside sections of the back are opened to remove the drums for loading and are held in an open position by a latch which folds against the side of the camera housing.

The two microswitches, mounted on either side of the camera, and two rotating sectors, which provide synchronization of the drums with the explosion are also visible in Fig. 19 [see Sec. 6.3(b)].

The camera shutter consists of two metal strips that slide in guides mounted on a metal rack panel. The shutters are shown in the opened position in Fig. 18. The metal panel fits tightly against the bakelite camera housing. The shutter handle, which can be seen at the top of the figure slightly to the left of the hinges on the mirror door, is attached to the shutter by a flexible cable, which can be seen between the two pairs of lenses. Another handle is located at some distance from the camera so that the shutter can be operated by the same person controlling the switch which detonates the explosion. A spring is attached to the shutter to keep it closed.

Referring to Fig. 18, it can be seen that the four 3-in. cathode-ray tubes protrude farther from the cathode-ray-tube panel than do the 5-in. tubes. This is necessary because, although the 5-in. tubes are focused on the axis of the lens, the 3-in. tubes are focused off-axis, and consequently, since the film is attached to a curved drum, the optical path between the lens and the film is different for the two different tube locations. The 3-in. tubes are moved closer to the lens than the 5-in. tubes in order to compensate for this difference in the lens-to-film distance.

Two lever-type catches are provided on the door to which the mirror is attached to keep it closed. The mirror supports are arranged so that the mirrors can be tilted to line up the optical system. The compartment in which the front of the camera, the tubes, and the mirror, are contained is light-tight. A viewing hole, not visible in the figure, is provided in the light-tight compartment just behind the central support on the mirror door hinge.

This camera has been operated at drum speeds from 1 revolution in 33 msec to about 1 revolution/sec. Its operation has been extremely satisfactory.

(c) Rotating-drum camera for use with DuMont type 208 oscillograph. — Figure 20 is a line drawing of an assembled rotating-drum camera which is used for photographing two DuMont type 208 oscillographs. The oscillographs are placed on a table and the camera is either mounted on a table by support CS, or mounted in the wall of a darkroom by brackets B.

The light-tight tube MT is hinged at the oscillograph and fastens to the tube T that contains the shutter and fits over the camera lens. The light-tight tube contains a viewing tube V and a mount for a crater lamp (TT) used for simultaneous timing [see part (a) of this section]. The shutter S is a sliding metal plate.

When the camera is used with only one oscillograph, the tubes MT and T are replaced by a light-tight tube which contains a flap shutter and is similar to the one used in the cut-film camera described in Sec. 8.3.

The details of the drum and lens assembly are shown in Fig. 21. The camera consists of a metal box with a hinged top and back. The lens is mounted on the front of this box and the drum, which is similar to those described in part (a) of this section, although it does not contain flanges and cannot be readily removed, rotates on a ½-in. shaft, one end of which extends through the side of the camera. The camera box is divided into two compartments, one of which is light-tight and contains the drum, and another which houses a rotating viewing prism. A sheave on the drum shaft is connected to a 1/50-hp induction motor by a belt. The particular camera shown here was designed for use with only one oscillograph so that the lens-to-drum distance shown in the figure is not correct for use with two oscillographs.

When the camera is attached to only one oscillograph, use can be made of the glass viewing prism P (made by Central Scientific Company). This prism, which rotates with the drum shaft, gives a rough time base for viewing the oscillograph screen while recording, and by means of the prism an experienced operator can observe considerable detail on the oscillograph record. The prism is viewed through the viewing tube V (Fig. 21).

These cameras have been operated up to maximum speeds corresponding to 15 msec per revolution, although at very high speeds it is probably advisable to remove the viewing prism. The drums could be loaded more easily if they were constructed along the lines of the newer type described in (a), which have flanges. These cameras have operated satisfactorily for over three years.

8.5. Films for the photography of cathode-ray tubes

Since the use of a fast film is the least expensive method of obtaining high writing speeds, fast films are desirable for the photography of high-speed transients on cathode-ray tubes. When high writing speeds are not required, however, the use of recording papers simplifies photographic processing.

A number of considerations are involved in the choice of the proper film for transient cathode-ray tube photography [38]. Among these considerations probably the most important, aside from film speed, are the relative spectral characteristics of the film and the cathode-ray-tube screen [see Sec. 7.2(c)]. The exposure time also influences the choice of film, since the sensitivity of a film is a function of the exposure, and the development procedure may affect the relative merits of different films.

No careful study to determine the optimum film for cathode-ray-tube photography has been made at this laboratory and unfortunately, although a number of independent investigations have been conducted [37 to 41], the information available on this subject is not complete. The following films, listed in order of preference, have been used at UERL:

Cut films: (1) Eastman Super-Panchro Press Type B, (2) Eastman Tri-X Panchromatic, (3) Eastman Ortho-X.

35-mm films: (1) Eastman Fluorographic (green sensitive, X-ray), No. FO-402, (2) Eastman Super-XX, (3) Eastman Plus-X. Fluorographic is preferred because, unlike most films, the back-ground on the developed film is perfectly clear and a record is much more easily discerned on a negative with a clear background than on one which is even slightly opaque.

8.6. Photographic processing techniques and equipment

The developing procedures which must be used under field conditions are far from ideal and thus the developers recommended by the manufacturers are not always best suited for the particular conditions at hand. Although Eastman D-19 is recommended for high contrast, it was found that less fogging occurred when films were developed with Eastman DK-60a than when D-19 was used.

Ordinarily the films are developed in DK-60a for the 10 to 12 minutes at 65°F. Under certain conditions the development time must be reduced to prevent fogging and extreme care must be taken, if reproducible results are to be obtained, to maintain the minimum development temperature at 65°, or to compensate by increasing the time of development. This seems to be particularly important with Fluorographic film.

Standard bakelite developing tanks are used for developing cut film, and in some cases for developing 35-mm film. The standard roll-film tanks are not well adapted to the 10-in. lengths of 35-mm film used, however, and special tanks have been constructed. The tank used in the Mobile Laboratory is shown in Fig. 22. It consists of three compartments, one each for the developer, water, and fixing bath, which can hold two of the film racks shown. The tank, made of bakelite and mounted permanently in the bench in the darkroom in the Mobile Laboratory (see Fig. 38), contains stopcocks along its bottom edge for draining the solutions. The film racks are made of lucite.

The film cutter shown in Fig. 23 is used for cutting the 35-mm film into 10-in. lengths. It was found necessary to use only one set of guide pins to hold the film because undeveloped film varies appreciably in length under different weather conditions. When the film cutter is used, the film reel is placed on a holder and the sprocket holes in the film are placed over the guide pins. The film is pulled taut, the top of the cutter pressed down, and both ends of the film are cut. Each end is cut to provide exact location of the sprocket holes relative to the ends, a precaution which greatly simplifies attaching the film to the drums.

Chapter 9

CALIBRATION OF THE BLAST-MEASURING EQUIPMENT

The accurate determination of the pressure-time curve from an explosion necessitates a precise knowledge of the pressure sensitivity and time resolution of the blast-measuring instruments. At UERL the pressure sensitivity is usually evaluated in two parts: the piezoelectric gauge sensitivity is determined in terms of the charge developed by the gauge for a unit change in the applied pressure; and the charge sensitivity of the cables, amplifiers, and so forth, is determined in terms of the deflection (on the film used to record the pressure-time curve) per unit charge. The gauges are generally calibrated infrequently but the remainder of the equipment is calibrated just before and after each measurement of a blast wave.

The time resolution on the record of the pressure-time curve is determined in terms of the deflection (on the film) per unit time. A timing calibration is applied while, or immediately before, the recording is made.

It is generally considered desirable to obtain blast measurements accurate to 1 percent, which requires that the standards used for calibration should be accurate to about 0.5 percent. When blast pressures are determined by shock-wave propagation-velocity measurements, however, it is necessary to use timing calibrations which are accurate to about 0.05 percent or 0.1 percent, since the accuracy required in the velocity measurements is much greater than that obtained in the pressures calculated from those measurements.

The fundamental units to which all blast measurements are referred are length, mass and time. Pressure is determined in the last analysis by reference to a dead-weight tester, which involves a knowledge of mass (or weight) and length. The electrical units such as voltage and capacity are required only to be self-consistent and it is not necessary to refer these units to an absolute standard. Time is determined by reference to the Bureau of Standards by means of radio station WWV.

9.1. Calibration of the gauge sensitivity

The sensitivity of a piezoelectric gauge is determined by measuring the charge developed by the gauge when either a static or dynamic pressure pulse is applied to it. A static pressure pulse is one in which negligible mass flow takes place around the gauge, and a dynamic pressure pulse is one in which the flow of air around the gauge is appreciable. As has been pointed out in Chap. 1, the sensitivity of a gauge to dynamic pressures is, in general, lower than its sensitivity to static pressure. Detailed information on the behavior of a gauge exposed to dynamic pressures is presented in Refs. 8, 23, 24 and 44.

The static sensitivity of a tourmaline gauge is directly proportional to the piezoelectric constant of the tourmaline, $\underline{K}$, and to the total area of the electrodes, $\underline{A}$. At this laboratory it has been the practice to denote the gauge sensitivity by $\underline{KA}$, expressed in the units of $\mu\mu$coulomb/(lb/in^2).

The discussion included here will deal primarily with the electronic equipment used in the calibration of gauges; details concerning the techniques described briefly in the following, and certain other methods which are not discussed, will be found in Ref. 8.

(a) Static calibration of gauges. — At this laboratory a static calibration of a gauge is ordinarily obtained by placing the gauge in a compression chamber filled with paraffin oil which is subjected to a known air pressure. When the pressure in the chamber is released, the charge developed by the gauge is determined by the circuit shown schematically in Fig. 24.

This circuit, developed by Roberts [46], is called a microcoulometer, and is used in essentially the same manner as is a ballistic galvanometer. It consists of a highly degenerative current amplifier with a high input resistance and with a provision for reading the output directly on a microammeter. The gauge output is connected to the terminal marked G in the figure, which applies a signal to T_1, a voltage amplifier. Tube T_2 serves as a current amplifier for producing a deflection on the microammeter and is also connected to the grid circuit of T_1 (between the low side of the input and ground) to provide a considerable amount of negative feedback. A battery in the cathode circuit of T_2 is used to balance out the zero-signal current in the microammeter and the zero on the meter is adjusted by R_1.

The microcoulometer actually measures the voltage developed across a condenser connected to the input so that the measurement of charge depends on the value of this condenser. The sensitivity is controlled by changing the amount of negative feedback and may be varied from 0.3 μamp/mv to 2.5 μamp/mv. On all ranges except the one of highest sensitivity the feedback is sufficient to eliminate, within 1 percent variations in all circuit parameters except the microammeter, the external condenser, and the feedback resistors in the grid circuit of T_1. Although, by employing precision resistors and condensers, and by using a calibrated microammeter, it is possible to measure charge to 1 percent with this circuit, in practice use has not been made of this fact and a calibration is always applied to the instrument. If a calibration is not made, a small correction can be applied to the unit when it is used on the most sensitive range [29, 46].

When the instrument is used to calibrate a gauge, two good-quality mica condensers are inserted in the terminals marked SC and PC in the figure. Condenser SC is used as a standard of capacity, and condenser PC is used as a padding condenser to increase the input time constant of the instrument. When the charge developed by the gauge is to be measured, the switch S_3 is thrown to "calibrate" and the deflection of the microammeter is read when the pressure in the calibration chamber is released. The instrument itself is calibrated by throwing switch S_3 to "standardize" and then applying a known voltage by closing switch S_4 and reading the deflection of the meter. The charge developed by the gauge is then given by

$$Q = C_S V_S \frac{I_G}{I_S}, \tag{9.1}$$

where

Q = charge developed by gauge
C_S = capacity of standard condenser (SC)
V_S = voltage applied at S
I_G = deflection of microammeter when gauge is calibrated
I_S = deflection of microammeter when microcoulometer is standardized.

The derivation of this equation, which involves the charge-calibration method used throughout in UERL equipment, is given in Sec. 9.2(c). Thus the charge developed by the gauge when subjected to a change in pressure is determined by measuring the ratio of the deflections on the microammeter caused by both the gauge signal and the standardization signal. The values of the standard voltage and the standard condenser must be known. The standard voltage is obtained from the General Radio precision-resistance divider and is measured by connecting a potentiometer to the top of the divider. The potentiometer and standard condensers used are described in Sec. 9.2(a) and (b).

The period of the microammeter used in this circuit must be sufficiently small for the meter to reach full deflection before the adiabatic expansion of the oil in the compression chamber causes a pyroelectric signal to develop in the gauge. The time constant of the input circuit must be long compared to the period of the meter and the time required for the pressure to drop in the compression chamber. These considerations are discussed in Ref. 8. The microammeter used is a 50 μamp meter (Model "University" made by the Sensitive Research Instruments Corporation) with a period of about 1 sec and a resistance of about 2200 ohms.

The operation of the microcoulometer circuit is affected by the plate-supply voltage and by leakages in the input circuit. These two factors have caused difficulty at this laboratory as well as at others, but the circuit shown in Fig. 24, of which two units were built, has been entirely free from these problems and has not required careful alignment or extensive servicing. In this circuit plate-supply fluctuations are eliminated by the use of an electronically regulated power supply and the input circuit has been mounted on lucite to reduce leakage.

(b) Dynamic calibration of gauges. -- Dynamic gauge calibrations are obtained by measuring the pressure recorded by a gauge when subjected to a shock wave of known amplitude. The shock may be produced either by an explosion or by the "shock tube," which consists of a long cylindrical tube divided into two parts by a thin (cellophane) diaphragm. One part, called the compression chamber, is pumped full of air which, when the diaphragm is punctured, is released into the second part, known as the expansion chamber, in which the gauges to be tested are placed. The bursting of the diaphragm produces a compressional wave in the expansion chamber which rapidly builds up to a shock wave. The shock tube is described in detail in Refs. [8, 44 and 47.]

9.2. Calibration of the charge sensitivity of the recording equipment

The most obvious method, although not the simplest, of determining the charge sensitivity of the recording equipment involves the separate calibration of the voltage sensitivity of the amplifiers and recording device, and of the capacity of the gauge cable and gauge. This was the original technique used at UERL, but a more recent type of calibration provides a single determination of the over-all charge sensitivity of the equipment. Both methods will be presented in the following.

(a) Calibration of voltage sensitivity. — The conventional method of determining the voltage sensitivity of an amplifier or cathode-ray oscillograph involves the use of a sinusoidal voltage. The sinusoidal voltage is also used at times as a timing calibration. This method is unsatisfactory for a number of reasons: (1) Since it is difficult to measure accurately the distance between two points along a line which does not join the two points, the successive cycles of a sine wave have to be very close together if their amplitude is to be measured accurately. This requires that the frequency of the calibration voltage be high compared to the frequency of the time base and the calibration frequency may have to be changed for different time-base frequencies. A frequency of 10 kc/sec or higher is probably necessary to obtain accurate measurements on sweeps of a few milliseconds duration, which are the sweep speeds used for the measurement of blast from small charges. (2) Although a high-frequency wave is more easily measured on the oscillogram than one of low frequency, the higher the frequency the less reliable are the readily available voltmeters. (3) The source of voltage must be extremely stable over short periods because the voltage read on a meter is an average value whereas the photograph records an instantaneous value. (4) From a fundamental point of view, the most appropriate type of calibration to use with equipment intended for measurements of transients is a transient, rather than a sinusoid. Thus, although sinusoidal voltages were used for calibration when the study of underwater shock waves was first begun at this laboratory, this type of calibration was discarded at an early date.

It has been the practice at this laboratory to use a unit-step voltage for amplitude calibrations instead of a sinusoidal voltage. A unit-step voltage is an instantaneous change in potential from one fixed value to another. The advantage of a step-type amplitude calibration from a fundamental point of view is that, since it is a transient pulse, it provides a measure of the transient response as well as of the sensitivity of the recording equipment. A step pulse is very easily measured on the oscillogram and the magnitude of the calibration voltage can be accurately determined with a potentiometer. A mechanically generated square wave has been used by the Stanolind Oil and Gas Company for providing amplitude calibrations. Its advantage is that synchronization of the beam-brightener or sweep-generator is not required. This method, however, does not provide a true representation of the transient response of the recording equipment. See Appendix B.

A step-voltage generator for use in blast measurements should include an adjustable source of voltage, a switching device, and a synchronizing circuit. The synchronizing circuit initiates the beam-brightener or the sweep-generator before the switching device operates so that a zero line is provided to which the deflection on the oscillogram can be measured.

How closely a step generated by a practical circuit approaches the instantaneous change in voltage of an ideal step depends on four factors: (1) The speed with which the electrical circuit is broken; (2) the internal resistance R of the voltage source; (3) the capacity C across the output of the voltage source; and (4) the internal inductance L of the voltage source. A break contact is always used to generate the step in order to reduce chatter. If no inductance were present in the circuit and if the switching device operated instantaneously, the voltage across the output would build up exponentially with a time constant RC. The effect of the inductance is to cause the voltage to build up more gradually at the very beginning of the pulse than would be the case in the RC circuit.

The greatest time of rise which is permissible depends, of course, on the frequency range of interest in the blast measurements, but it also depends on the use to which the step calibration is to be put. If the step is not to be employed as an indication of the high-frequency response of the equipment, the only requirement on the rise time is that it be sufficiently small to produce a reasonably square step, because a rounded step is somewhat difficult to measure. If, on the other hand, the calibration step is to be used as an indication of the high-frequency transient response of the recording equipment, the rise time must be negligibly small in comparison to the shortest times of importance in the pressure waves to be measured. For most air-blast measurements very little trouble is encountered in obtaining a sufficiently rapid rise time but, since shock waves in water are a much higher frequency phenomena than shock waves in air, a lower impedance voltage source is required for the former than for the latter.

(i) Voltage sources and voltage standards. The voltage source used to obtain a step calibration in air-blast equipment is a dry cell to which is connected a resistance divider. Burgess Type 4FA or 4FH "Little Six," $1\frac{1}{2}$-v dry cells, or No. 6 cells of other manufacture, are used. These batteries are connected to a precision resistance divider which draws 1 ma. The batteries will maintain a very constant output voltage under these conditions if they are treated with reasonable care. The maximum variation in the voltage from two of these batteries over a period of four months in which daily measurements were made was 3/4 percent. This variation was attributed to changes in the ambient temperature, which varied from 55°F to greater than 95°F. These temperature measurements were made in the control room; the actual temperature in the neighborhood of the batteries was undoubtedly higher than this upper limit. The lower limit is probably correct, however. The voltage always increased with the rise in the ambient temperature which occurred after the equipment was turned on.

The resistance divider used with the battery provides a balanced output voltage which can be varied from 1 mv to 1.45 v in 3db steps. The divider is made up of 24 wire-wound precision resistors. [See Sec. 10.2(b)].

The impedance of these dividers is rather high and consequently, if they are to be used to test the response of the recording equipment to high-speed transients, the capacity across the output of the divider must be kept small. The impedance of the divider is limited by the current which can be drawn from the dry cell without affecting its stability because, in order to prevent excessive chatter in the switching circuit, it is necessary to use a break contact rather than a make contact, and thus the divider is connected to the battery except for the duration of the step.

The design adopted here is undoubtedly conservative, but the divider impedance is adequate for most air-blast measurements. When an accurate low-impedance source of voltage is required, as in the study of underwater explosions, a gaseous voltage-regulator tube can be used [33], although the use of these tubes is rather complicated and no reasonably simple method of obtaining a balanced step voltage from them has been proposed. Voltage-regulator tubes are not considered to be as reliable as dry cells.

The battery voltages and the output of the voltage divider are measured with a Rubicon Potentiometer, Cat. No. 2700. This instrument has been found very satisfactory, particularly because it has sufficient range to measure accurately both the 1.5 v battery output and the voltage divider outputs. The potentiometer is periodically checked against a standard cell used only for this purpose. An electronic potentiometer [see Sec. 10.2(d)], which has an accuracy of about 3/4 percent, is built into the control equipment and is used to check the battery voltage a few times a day. The actual step output voltages are usually determined from the battery voltage by using the calibration of the resistance divider, but at least once during every test program, and usually more often, the step voltages are measured directly with the Rubicon potentiometer. No appreciable variation has occurred in these dividers over a considerable period of time.

(ii) Circuits for generating a step voltage. The fundamental requirements of a switching circuit for generating a step pulse is that it provide rapid and chatter-free interruption of the electrical circuit containing the voltage source. The step-generating circuit is also required to produce a trip pulse, occurring at a preassigned but adjustable time before the step pulse, to synchronize the step with the sweep-generator or beam-brightener. Mechanical, electro-mechanical and electronic step-generators have been used.

Mechanical switches of any type are always accompanied by chatter, which is particularly noticeable on an oscillogram of high resolution, and if the contacts are exposed to dust the chatter is likely to be very troublesome and erratic. Since the chatter occurring when a contact is made is much greater than when a contact is broken, break contacts are always used in step-generating circuits. Thus electronic switching is preferable, but it is considerably more complicated than electro-mechanical or mechanical switching.

Considerable experience with the use of step-generators in blast measuring equipment has indicated that it is extremely desirable to be able to trip the step-generator at the same time that the cathode-ray tubes are being observed. In order to do this it is necessary to have the tripping mechanism of the step-generator at some distance from the generator, because, when a number of channels are operated from one step-generator, the step generator cannot usually be located within reaching distance of all the cathode-ray tubes. The additional circuit complications necessary to provide remote tripping are compensated for many times over by the increased speed and convenience with which the recording equipment can be operated. This requirement makes purely mechanical step-generators unsatisfactory.

Both electronic and electro-mechanical step-generators are now in use at UERL. The electronic step-generators, which are used in the equipment for the study of underwater shock waves [33], provide excellent chatter-free steps with a fast rise time, but the circuit used cannot be readily adapted to provide balanced output voltages and consequently has not been employed in air-blast equipment. The electro-mechanical step-generators use a hermetically sealed relay, controlled by an electronic time-delay circuit, as a switching device. Although relay-type step-generators have proven to be satisfactory for air-blast measurements, they are not completely adequate for testing the high-speed transient response of the recording equipment. The relay-type step-generators are unsatisfactory for high-speed recording because of the inevitable chatter present in a mechanical switch and because the relay contacts do not open rapidly enough. Relay step-generators have not been made to operate reliably without chatter at sweep speeds faster than 0.4 msec/in. on the oscillograph screen, and careful adjustment is required to eliminate chatter at speeds of 1-2 msec/in. A step generator of the relay type is described in Sec. 10.2(c).

Mechanical step-generators have also been used. The simplest of these is perhaps the spring rheotome, described in Sec. 6.3(a). Spring-actuated rotating switches have also been employed. Both of these devices were unsatisfactory because they were subject to chatter and were very inconvenient to operate.

(b) Calibration of the capacity in the gauge circuit. -- The capacity of the gauge and gauge cable is most readily determined by means of a capacity bridge. In field use, however, when a bridge is not always available, it is possible to determine the gauge circuit capacity by comparing it, in a capacity-divider circuit, with a good quality condenser of known value. The capacity-divider technique is particularly useful because it provides a means of measuring the time constant and the dielectric absorption in the gauge circuit.

(i) Capacity standards and capacity bridges. The standard of capacitance at this laboratory is a General Radio type 716-B capacitance bridge. This bridge has an accuracy of $\pm$ 0.1 percent of full scale. It is checked periodically against General Radio type 509 precision mica condensers, which are accurate to 0.1 percent. An inter-laboratory comparison between those laboratories using tourmaline piezoelectric blast gauges has also been made in order to correlate gauge-calibration data [8].

A specially designed capacity bridge was loaned to this laboratory by K. S. Cole [48] and was used, over wide frequency ranges, for the measurement of dielectric dispersion in cables.

Less accurate bridges have also been constructed for use as an integral part of the recording equipment employed in the study of underwater shock waves [33].

The condensers used as standards in a capacity divider network and as padding condensers are General Radio type 505 mica condensers. These condensers, which are guaranteed to be within 1 percent of their rated value, are of good construction, have a high leakage resistance, a very small amount of dielectric absorption, and a low temperature coefficient of capacity. As pointed out below, high leakage resistance and freedom from dielectric absorption are characteristics which are extremely important in a condenser for use as a standard in blast measurements. Difficulty has been encountered with some of these condensers when they are exposed to wide temperature variations: differential expansion between the case of the condenser and the filling material causes the seal between the two to break and moisture enters the condenser, increasing the leakage. The manufacturers investigated this difficulty and recent condensers have been improved.

(ii) Capacity-divider method of capacity calibration. The capacity-divider method (sometimes called the capacity-step calibration) is illustrated in Fig. 25(b). Here C_C represents the total unknown capacity and C_S represents the standard condenser to which comparison is to be made. C_C is equal to the parallel combination of the cable capacity, the gauge capacity, the padding capacity (if any) and the stray capacity. V_S is a standard voltage which is applied to the capacity-divider and V_C is the output voltage applied to the detector. Usually V_S is a step voltage obtained from a step-generator and V_C is applied to the amplifier of the recording system, and although this arrangement is not necessary, it permits the determination of the stray capacity in the gauge circuit as it exists during the recording of the blast wave. If it is assumed that the leakage resistances R_C and R_S are infinite, the output voltage V_C is given by

$$V_C = \frac{C_S}{C_C + C_S} V_S \qquad (9.2)$$

so that the unknown capacity C_C is given by

$$C_C = \left(\frac{V_S}{V_C} - 1 \right) C_S. \qquad (9.3)$$

In practice the deflection sensitivity of the oscillograph, a_o, (in terms of the deflection on the film for a unit change in potential applied to the input of the amplifier) is determined by means of a voltage step. Thus, if d_S' is the deflection measured on the film which corresponds to the voltage step of amplitude V_S', $V_S' a_o = d_S'$. Similarly, if d_C is the deflection due to V_C, $V_C a_o = d_C$ and

$$V_C = V_S' \left(\frac{d_C}{d_S'} \right). \qquad (9.4)$$

Thus the unknown capacity is given in terms of the ratio of the two standard voltages, the two deflections and the value of the standard condenser by the relation

$$C_C = C_S \left[\frac{V_S d'_S}{V'_S d_C} - 1 \right] \tag{9.5}$$

where

C_C = capacity in gauge circuit

C_S = standard capacity

V_S = standard voltage applied to capacity divider

V'_S = standard voltage applied to amplifier

d'_S = deflection (on film) of voltage step applied to amplifier

d_C = deflection (on film) of output of capacity divider

The capacity divider method of determining the cable capacity forms the basis of the over-all charge sensitivity calibration and it provides a means of measuring the time constant and dielectric absorption in the gauge circuit. It can also be used on balanced cables, as described in the following section.

(c) Over-all calibration of the charge sensitivity.* — Instead of making two separate sensitivity calibrations, one of the voltage sensitivity of the recording equipment, and one of the capacity in the gauge circuit, it is possible to obtain a complete charge calibration from only one operation. This calibration technique determines the over-all sensitivity of the recording equipment to the charge developed by a piezoelectric gauge. It also provides a means of measuring the complete transient response of the recording system. In case long gauge lines are used the charge calibration step does not indicate the response of the cable at high frequencies. See the following. The charge calibration step has been adopted at this laboratory for all routine amplitude calibrations of piezoelectric blast-measuring equipment.

(i) Use of the charge calibration step to determine the charge sensitivity of the recording equipment. When the system is calibrated by the charge-step method, exactly the same circuit is employed as is used in the capacity-calibration step described above. When the gauge signal is recorded, however, the standard condenser, instead of being disconnected from the circuit, is connected in parallel with the cable capacity.

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*The equipment used to obtain a charge calibration step is described in Chap. 10.

The circuit used when the gauge signal is to be recorded is shown in Fig. 26(a). The application of a pressure P to a gauge with pressure sensitivity (KA) produces a charge Q on the electrodes of the gauge. Thus a charge

$$Q = (KA)P \tag{9.6}$$

is developed by the gauge and is applied to the cable and amplifier. The total capacity in the gauge circuit is the sum of the cable capacity, gauge capacity, and so forth, C_C, and that of the standard condenser, C_S. The voltage V_P developed across the terminals of the amplifier by the action of the pressure P on the gauge is, therefore, provided the leakage resistances R_C and R_S are infinite, given by

$$V_P = \frac{Q}{C_C + C_S} = \frac{(KA)P}{C_C + C_S} \tag{9.7}$$

or

$$P = \frac{(C_C + C_S)\ V_P}{(KA)} \tag{9.8}$$

If a_o is the deflection sensitivity of the amplifier and recording device in terms of the deflection on the film for a unit change in potential applied to the input of the amplifier, the deflection d_P produced on the film by the voltage V_P is $d_P = a_o V_P$. Thus

$$P = \frac{C_C + C_S}{(KA)}\ \frac{d_P}{a_o} \tag{9.9}$$

If a capacity-calibration step, similar to that described in the last section, is applied to the system by inserting a step voltage of amplitude V_S into the circuit as shown in Fig. 25(b), a step output voltage is obtained of an amplitude given by Eq. (9.2) of the last section. If we rewrite this equation in terms of the deflection d_C produced on the film we have, on rearranging,

$$\frac{C_C + C_S}{a_o} = \frac{C_S\ V_S}{d_C} \tag{9.10}$$

Substituting Eq. (9.10) in Eq. (9.9) we have

$$P = \frac{C_S\ V_S}{(KA)}\ \frac{d_P}{d_C} \tag{9.11}$$

where: P = pressure applied to gauge (lb/in²)
C_S = standard capacity ($\mu\mu f$)
V_S = standard calibration voltage (volts)
(KA) = gauge sensitivity = calibration constant [$\mu\mu$coulombs/(lb/in²)]
d_P = deflection (on film) due to pressure P
d_C = deflection (on film) of calibration step

The quantity $C_S V_S$ in Eq. (9.11) can be interpreted as a standard charge and the capacity of the gauge circuit has been eliminated.

Thus the pressure in the shock wave can be determined in terms of a known capacity, a known voltage, the calibration constant of the gauge, and the ratio of the deflection of the blast record to the deflection of the calibration step.

(ii) Use of the charge-calibration step to determine the transient response of the recording equipment. If the leakage resistance of the standard condenser is sufficiently high, the charge-step calibration can be used to determine the time constant of the recording system. The leakage resistance across the standard condenser R_S, and the leakage resistance across the remainder of the gauge circuit, R_C, cannot be considered to be in parallel when the calibration is applied. Referring to Fig. 25 (a), if a step pressure wave, P(t), is applied to the gauge, the output voltage, $V_P(t)$, including the effect of the leakage resistances, is given (see also Ref. 8, Appendix IV) by

$$V_P(t) = \left(\frac{(KA)\,P}{C_C + C_S}\right) e^{-\frac{t}{x}} \tag{9.12}$$

where

$$x = \left(\frac{R_C\,R_S}{R_C + R_S}\right)\left(C_C + C_S\right) = \text{time constant of gauge circuit}$$

The output $V_C(t)$ of the circuit in Fig. 25 (b) when a step voltage $V_S(t)$ is applied is

$$V_C(t) = \frac{C_S\,V_S}{C_C + C_S}\left[\frac{x}{R_S\,C_S} + \left(1 - \frac{x}{R_S\,C_S}\right) e^{-\frac{t}{x}}\right] \tag{9.13}$$

These equations reduce to Eqs. (9.7) and (9.2) respectively when t is small compared to x. There are three special cases of Eq. (9.13) which are of interest:

(1) $R_S \gg R_C\,C_C/C_S$, that is, the leakage resistance R_S of the standard condenser is very large and $x/R_S\,C_S \ll 1$. Under these conditions the decay of the step calibration, as given by Eq. (9.13), is the same as the decay of the voltage from the step pressure pulse, given by Eq. (9.12). Thus, if the leakage resistance of the standard condenser is very high, the time constant of the decay of the charge-calibration step is the same as the time constant of the circuit as seen by the gauge.

(2) $R_S = R_C\,C_C/C_S$. Under these conditions $x/R_S C_S = 1$, Eq. (9.13) is independent of time and $V_C(t)$ is a pure step pulse. A circuit of this type is used frequently as a means of compensating an attenuator for frequency, since the response of the circuit is independent of frequency. It is used, for example, in the DuMont type 208 oscillograph (see Fig. 5)

(3) $R_g < R_c C_c/C_g$ that is, the leakage resistance of the standard condenser is relatively small and $x/R_g C_g > 1$. The output of the calibration step will then increase with time. Thus it is seen that only in case (1) is the response obtained from the charge calibration step equivalent to the response of the circuit to a step pressure signal, and consequently it is important to maintain a high leakage resistance in the standard condenser if the calibration step is to be used as an indication of the transient response of the recording equipment.

The long-time transient response of the amplifier is also recorded by the charge-calibration step, just as it would be by a voltage step applied directly to the amplifier. Similarly, the high-frequency response of the recording system, excluding the high-frequency response of the gauge and the gauge cable, are determined by the charge-calibration step. It is important to note that the transient response of a long cable is not ordinarily determined by this method, although it is possible to use a small standard condenser (about 100 $\mu\mu f$) at the transmitting end (gauge end) of the cable to approximate the internal impedance of the gauge, and thus also to determine the response of the long cable [26]. This technique, however, is not well adapted to routine measurements because: (1) it is inconvenient to apply a calibration step at the transmitting end of the cable; (2) the standard condenser must be so small in order to approximate the internal impedance of the gauge that its capacity cannot be accurately determined and consequently accurate amplitude calibrations cannot be obtained; (3) the leakage resistance of a small standard condenser must be very high to obtain the correct step response, as indicated by case (1) of Eq. (9.13). To obtain the correct high-frequency response it is necessary, of course, that the rise time of the step calibration voltage applied to the standard condenser be small compared to the smallest response time which is of interest in the recording equipment.

The dielectric absorption in the gauge circuit can also be evaluated by the charge-step calibration technique. If the standard condenser has no dielectric absorption, and if the leakage resistances in the circuit of Fig. 25 (b) are very high, the only part of the circuit which will cause the output to vary with frequency is the absorption in the gauge cables. Thus the output of the calibration step will vary with time in the same manner as the output of the circuit when the gauge is subjected to a step pressure pulse. The dielectric absorption of the General Radio type 505 condensers used in these circuits is small enough to make this method sufficiently accurate to be used for the quantitative correction of the pressure-time curve for dielectric absorption [see Sec. 4.1(3) and Ref. 26].

Thus the charge-calibration step determines, by one very simple operation, the charge sensitivity of the recording equipment and, excluding the high-frequency response of the gauge and the gauge cable, also determines the complete transient response of the system. The individual factors which determine the transient response are not determined separately, of course, but rather the net effect of all factors is evaluated simultaneously. In practice it is seldom necessary to use this quantitative information concerning the transient response because the response of the recording equipment is usually adequate. The method is used regularly, however, to give a very rapid and simple qualitative check of the operation of the equipment. It should be noted that, although the charge-calibration step gives an accurate measurement of the low-frequency response, it is not the most accurate method of obtaining the high-frequency response. (See Appendix B.)

(iii) Use of the charge calibration step in push-pull circuits. The charge-calibration step can also be used to determine the sensitivity and the transient response of a system involving balanced lines.

There are two methods of connecting a piezoelectric gauge to a balanced cable [see Sec. 3.2(b)]. One of these methods uses a Type 1 push-pull gauge in which none of the electrodes of the gauge are grounded. The circuit employed with this type of gauge is shown in Fig. 26. The other method, shown in Fig. 27, makes use of the Type 2 push-pull gauge. This gauge is grounded at its central electrode.

A balanced calibration voltage (centered about ground) and two standard condensers are used to calibrate both circuits. If the two sides of the balanced system are identical the pressure is evaluated, by means of the charge-calibration step, from the following exact equation (see Appendix C).

$$P = \frac{C_S \, V_S}{2(KA)} \frac{d_P}{d_C} \tag{9.14}$$

where P = pressure applied to gauge (lb/in.^{2})
$C_S = C_{S1} = C_{S2}$ = standard capacity in each side of circuit ($\mu\mu f$)
$V_S = V_{S1} + V_{S2}$ = sum of standard calibration voltages applied to both sides of circuit (volts)
$(KA) = (KA)_1 = (KA)_2$ = gauge sensitivity = gauge calibration constant on both sides of circuit in Fig. 27, equals total gauge sensitivity in Fig. 26. [$\mu\mu$coulomb/(lb/in.^{2})]
d_P = deflection (on film) due to pressure P
d_C = deflection (on film) of calibration step.

In all practical cases encountered the two sides of the system are balanced sufficiently to permit Eq. (9.14) to be used. This equation is usually correct within 0.5 percent, if the following substitutions are made: (1) Replace C_S by $\overline{C}_S$, the mean standard capacity, which is defined as

$$\overline{C}_S = \tfrac{1}{2}(C_{S1} + C_{S2}) \tag{9.15}$$

where C_{S1} = standard capacity in side (1) of circuit ($\mu\mu f$)
C_{S2} = standard capacity in side (2) of circuit ($\mu\mu f$)

(2) If the Type 2 push-pull gauge is used (Fig. 27), replace (KA) by $(\overline{KA})$, the mean gauge-calibration constant, defined by

$$(\overline{KA}) = \tfrac{1}{2}\left[(KA)_1 + (KA)_2\right] \tag{9.16}$$

where $(KA)_1$ = gauge calibration constant in side (1) of circuit [$\mu\mu$coulomb/(lb/in^2)]

$(KA)_2$ = gauge calibration constant in side (2) of circuit [$\mu\mu$coulomb/(lb/in^2)]

When Eq. (9.14), modified by Eqs. (9.15) and (9.16), is employed, the two standard condensors should be equal within 1 to 2 percent, the calibration voltages on the two sides of the circuit should be equal within about 1 to 2 percent, and the gauge constants on the two sides should be within 5 to 10 percent of each other. These limits are readily obtained in practice. The exact equations are given in Appendix C.

It is interesting to note that, for a given area of tourmaline, the Type 1 push-pull gauge (Fig. 26) is twice as sensitive as the Type 2 push-pull gauge (Fig. 27). If a Type 1 push-pull gauge and an ordinary single-ended gauge of the same size are connected, respectively, to a twin-ax cable and a co-axial cable of the same equivalent capacity, the effective sensitivity of the push-pull gauge will be twice that of the single-ended gauge.

9.3. Timing calibration of the recording equipment

The calibration of the time axis on an oscillogram is accomplished by measuring the displacement between successive cycles of a known frequency wave that is resolved by the same time base used to resolve the blast record. When single-sweep generators are used with fixed-film cameras, it is customary to obtain a calibration of the time base by photographing a single-sweep of a timing wave applied to the signal axis, and when moving-film cameras are employed a light source modulated at a known frequency is photographed on the film at the same time the oscillogram is recorded.

The timing waves used at this laboratory are usually generated by a fixed-frequency oscillator from which various other fixed frequencies are obtained by frequency division. The output of the frequency divider is shaped into short duration spikes which are either photographed directly as a deflection on the cathode-ray tube or are used to modulate a light source. Short duration spikes are used because they provide a sharp mark to which measurements can easily be made.

(a) Timing standards and primary oscillators. — The fundamental requirement of a timing source is that it be stable under all conditions of operation.

The frequency of the timing wave is usually chosen to be no higher than necessary to obtain sufficient accuracy over the interval in which the oscillogram is being measured, which, for records of pressure-time curves, corresponds to a maximum of about three to four cycles for the interval corresponding to the positive duration of the pressure wave. The lowest frequency possible is used because it takes considerable time to count a large number of cycles and because the higher the frequency the higher must be the intensity of the light source supplying the timing marks. Obviously, if the frequency of the timing wave is too high compared to the speed of the time base, it is impossible to resolve the timing marks. The timing frequencies used in UERL air-blast equipment are 125, 250, 500 and 1000 cps. These frequencies have proven adequate for most purposes, but the measurement of shock-front propagation velocity requires timing frequencies of about 5 to 10 kc/sec, and 1000 cps is insufficient for the recording of pressure-time curves from small charges at high pressures.

A crystal-controlled oscillator is employed when the highest accuracy is necessary, as for example, when precise velocity measurements are to be made. Since the lowest frequency crystal available at reasonable cost has a frequency of 100 kc/sec, considerable frequency division is necessary for a crystal to be useful for air-blast measurements. Multivibrators have been used for this purpose. The multivibrators and crystal oscillators used are described in Ref. 33.

When the accuracy and high frequency of a crystal oscillator are not required, tuning forks have been employed. The standard source of the timing waves used in air-blast equipment at UERL is a General Radio type 813-A audio oscillator, which is a 1000 cps tuning fork. The frequency of the tuning fork is calibrated to 0.1 percent; the temperature coefficient of frequency is -0.008 percent per degree F., and the dependence of frequency on the voltage used to drive the fork is 0.01 percent per volt. Thus the frequency stability of the tuning fork is sufficient for all ordinary blast measurements* and the effective accuracy can be increased by measuring the temperature of the fork. Although the tuning fork is very stable when in a level position, the frequency depends slightly on the orientation of the fork, although not to as marked extent as in forks of lower frequency. This is not objectionable for use in air-blast measurements, but is troublesome when the forks are used in a boat and consequently are not always level. The frequency of a tuning fork may be altered temporarily when the fork is subjected to shock or vibration, but no permanent effect has been observed when the intensity of the shock is not great enough to damage the electronic recording equipment.

A frequency divider is used with the 1000 cps tuning forks to obtain frequencies down to 125 cps. The frequency divider circuit employed is described in the following.

The primary frequency check is obtained by comparison of the crystal oscillators with WWV, the Bureau of Standards radio station. The crystal controlled multivibrators are set by beating them with the 5 mc/sec carrier from WWV and the tuning forks are calibrated by beating them with a calibrated multivibrator. During field use it has generally been found sufficient to check one tuning fork against another, although, if very accurate frequencies are required, it is desirable to have a means of checking against WWV or a crystal oscillator.

(b) Types of timing signals. — The calibration techniques employed for timing sweep-generators and moving-film time bases are somewhat different. In all blast measurements made at this laboratory, sweep-generators are calibrated by the application of a timing signal to the signal axis of the cathode-ray tube, and moving-film time bases are calibrated at the same time the oscillogram is recorded by means of either a cathode-ray tube or a modulated flasher tube.

*Including most velocity measurements.

The timing calibration of sweep-generators at the same time the pressure-time curve is photographed is not a trustworthy procedure because a certain number of records are bound to be made unreadable by interference from the timing marks. Simultaneous calibration is not necessary for the measurement of blast pressures, however, because sufficient accuracy can be obtained by calibrating the sweep-generator immediately before the oscillogram is recorded. The timing calibration is usually made previous to the occurrence of the blast because it is possible that the sweep speed could be changed by the impact of the blast on the equipment. Two types of timing signals are possible for use with cathode-ray tubes: a signal can be applied to the deflection plates of the tube or the beam intensity can be modulated. Since beam modulation requires a circuit for mixing the timing wave and the beam-brightener signal, and since this method does not offer any particular advantages, the deflection-type timing signal is preferred.

The timing signals used at this laboratory are all short duration spikes. The spikes are easily measured because they provide a clearly defined discontinuity. A sine wave, on the other hand, provides no such discontinuity, and is consequently difficult to measure. Sharp spikes are also used for driving flasher tubes.

The timing calibration of moving-film cameras [see Sec. 8.4(a)] is accomplished with either a cathode-ray tube or gaseous-discharge flasher tubes. Cathode-ray tubes are used in the same way that they are employed for the timing of sweep-generators. Gaseous-discharge tubes are driven by a short duration spike, usually of large amplitude, which is obtained from a low-impedance source.

(c) Circuits of timing-wave generators. -- Two types of timing units have been used for calibrating the time base of a cathode-ray tube. One of these units is operated by a 1000 cps tuning fork and provides output frequencies of 1000, 500, 250 and 125 cps. It is used for applying a deflection signal to a cathode-ray tube and can be used with either fixed- or moving-film cameras. The other unit is used to drive Sylvania Type 1B59 crater lamps and can be used only with moving-film cameras.

A third unit is used for timing in Eastman high-speed motion-picture camera. This timer, which is operated from a 1000 cps tuning fork, drives a neon lamp at 1000 or 500 cps.

(1) Timing unit for use in the Mobile Laboratory and with the DuMont type 208 cathode-ray oscillograph. The schematic circuit shown in Fig. 28 is used to provide timing pulses of 1000, 500, 250 and 125 cps. These signals may be applied directly to: (1) the cathode-ray tube deflection plates, as in the Mobile Laboratory; (2) to the voltage divider used for obtaining standard calibration voltages, and from the voltage divider through the recording amplifiers to the cathode-ray tube, as in the equipment used with the DuMont type 208 cathode-ray oscillograph; or (3) to the input of the unit, described below, which drives a crater lamp. The standard frequency of 1000 cps used to drive the timing unit is obtained from a General Radio Type 813-A audio oscillator (tuning fork).

The circuit consists essentially of two clipper stages (T_2 and T_3), three frequency-divider stages (T_4 to T_{12}) and two sets of output stages (T_{13}, and T_{14} and T_{15}). The frequency division is obtained from three counter circuits each of which divides the frequency by a factor of two. This type of circuit is fundamentally more stable than a multivibrator because a counter circuit does not oscillate unless a synchronizing signal is applied to it.

The output of the tuning fork connects directly to T_2. The output of the tuning fork itself contains a considerable amount of harmonics, but the output of the 813-A audio oscillator is filtered and harmonics are reduced to about 1 percent. Tubes T_2 and T_3 act as a conventional limiter, or peak clipper, providing an output wave form which approximates the shape of a square wave. Two tubes are used in order to obtain greater sharpness than can be achieved if only one clipper tube is employed. It should be noted that this type of circuit will convert amplitude modulation of the input sine wave to a frequency modulation of the output square law when the latter is differentiated. This effect can be made quite small if only a small fraction of the sine wave is passed by the clippers. The output of T_3 is differentiated and connected to the output stages to provide the 1000 cps output, and is also connected to the first counter circuit.

The three counter stages are identical. Each contains two tubes, such as T_5 and T_6, which act as a trigger circuit with two stable operating conditions, and one diode, such as T_4, which shunts out positive synchronizing signals. The synchronizing signals applied to the counter circuits, which are of very short duration, are obtained by differentiating the square wave from the preceding stage.

The operation of the counter circuits is as follows: A negative synchronizing pulse applied to the 750,000-ohm resistor common to the grid circuits of the two trigger-circuit tubes decreases the plate current in the conducting tube and applies a positive signal to the grid of the non-conducting tube, causing the nonconducting tube to conduct and the conducting tube to be cut off. If the bias on the nonconducting tube in sufficiently large, a positive signal will not trip the circuit. The counter circuit thus completes one cycle for every two negative synchronizing pulses, so that the output frequency is half the frequency of the synchronizing signal. Positive synchronizing signals are shunted by the diodes to insure that the circuit does not trip on positive pulses. The small condensers placed across the upper half of the resistance dividers in the grid circuits of the trigger tubes increase the transfer of the synchronizing signal between tubes at high frequencies. The divider in the cathode circuit is by-passed with a large electrolytic condenser in order to eliminate degeneration. The resistors in the trigger circuits were matched to within 2 percent to insure reliable operation.

Each counter circuit is connected to the output stages through a small condenser, and except for the last of these stages, each is connected to the diode of the next counter circuit. Since each of these circuits divides the input frequency by a factor of two, the output of the first counter circuit is 500 cps, the output of the second in 250 cps, and the output of the third is 125 cps. A different condenser is used to couple the 1000 cps clipper stage and each counter stage to the frequency selector-switch, S_1, and to the first output tube, T_{13}. These condensers are picked to obtain an output-pulse time constant as short as possible without decreasing the cathode-ray-tube spot intensity to such a low value that the pulses do not record on the photograph when the intensity is adjusted to the proper value to record the undisturbed zero line.

Tube T_{13} provides a small-amplitude timing signal that is applied to the standard voltage dividers in place of the calibration voltage. The amplitude is controlled by potentiometer R_1 to about 1.5 v peak-to-peak so that the amplitude of the timing pulses appearing on the cathode-ray tube will be about the same as the amplitude of the step calibration. The voltage divider is switched from the calibration battery and the step-generator by the master control (see Chap. 10). A 5-ma fuse is inserted in series with the divider to prevent short circuits in the timing unit from damaging the precision resistors in the voltage divider. Tubes T_{14} and T_{15}, connected to T_{13}, provide push-pull deflection for direct application of the timing signal to the cathode-ray-tube deflection plates. Spot centering is controlled by potentiometer R_3 and the mean potential of the deflection plates is determined by potentiometer R_2.

Tube T_1 is a tuning eye which is used to indicate if the output of the tuning fork is of sufficient amplitude to operate the circuit correctly. The eye closes at 20 rms volts signal and the circuit operates properly at 7 rms volts.

The timing unit, including the tuning fork, is built on a 17X13X3-in. chassis with a standard 7-in. rack panel. When the unit is used to supply a voltage divider, plate power at +300 v is obtained from a regulated power supply, and when the unit is used to deflect the cathode-ray tube directly power is obtained from a regulated power supply which supplies +300 and -200 v. This power supply is the master control power supply. See Sec. 11.3(a). The tuning fork power, at 6-v DC, is obtained from the master control DC supply [see Sec. 11.2(c)].

Two circuits of this type have been in use for a year and a half. They have given very satisfactory, trouble-free operation.

(ii) Unit for driving glow-modulator tubes. This circuit was designed for use in equipment for the study of shock waves in both air and water by the group at UERL primarily interested in the study of underwater explosions. The circuit of the unit used to modulate Sylvania Type 1B59/R1130B glow-modulator tubes for providing timing marks to calibrate moving-film oscillograph cameras is shown schematically in Fig. 29. The unit may be driven by a sinusoidal, square, or pulsed timing wave at frequencies from 125 to 10,000 cps. The circuit is designed to operate on input signals from 3 to 10 v, but a wider range of input signals operates the unit satisfactorily. The glow tubes are flashed only for the duration of the beam-brightener which controls the intensity of the cathode-ray tubes used to record the phenomena under observation. From one to eight crater lamps can be operated from the circuit. A typical mounting for the lamps in an oscillograph camera is shown in Fig. 20, Chap. 8.

Essentially the circuit has two inter-related functions: part of the circuit drives the crater tube and another part of the circuit acts as an electronic switch to prevent the timing signal from driving the crater tube except at those times that beam-brightener is tripped.

The circuit contains an amplifier (T_1), a limiter (T_2), and an electronic switch (T_3 and T_6) which are operated by the beam-brightener signal, and an amplifier-clipper (T_4), a limiter (T_5), and amplifier (T_6), in the circuit of the synchronizing timing wave. The output of the timing signal amplifier T_6 synchronizes the trigger circuit consisting of T_7 and T_8 which drives the output tubes with short-duration large-amplitude pulses.

Tube T_6 is cut off except when a beam-brightener signal is applied so that the timing wave from T_5 cannot synchronize the trigger circuit (T_7 and T_8). If a large signal is applied by T_6 to the trigger circuit when the beam-brightener is tripped, the grid circuit of T_7 will be blocked until the charge on the grid coupling condenser leaks off. To prevent this blocking action from affecting the circuit any longer than necessary the amplitude of the switching signal from T_6 must be kept to a minimum. The limiter (T_5) in the timing signal part of the circuit limits the timing signal applied to T_6 to a value below that which will affect the plate current of T_6 when the electronic switch is closed. The limiter T_2 in the beam-brightener part of the circuit reduces the possibility of damage occurring to T_3 from excessive positive grid voltage.

The trigger circuit T_7 - T_8 is a Schmidt type flip-flop circuit (see Appendix B) with a reset-time longer than the interval between timing pulses; thus it behaves as a trigger circuit instead of as a flip-flop. A circuit of this general type draws grid current when it is tripped, and after a few cycles of a repetitive synchronizing signal are applied the circuit will come to an equilibrium operating condition which is partly determined by the effect of the grid current on the condenser-coupled circuits. Between the first synchronizing pulse and the time when the circuit is operating in an equilibrium condition the amplitude of the output will change to an equilibrium value and the frequency of the output will change to the exact synchronizing frequency from some different frequency. Thus, if the first few cycles of the timing marks are to be of sufficient amplitude and of accurately known frequency, it is necessary to eliminate the effect of grid current. This is accomplished to a considerable extent by the 100-ohm cathode resistor between the grid return and the cathode of T_8 and by the constant bias voltage applied to T_7 by the divider to B. Except for the first two cycles the output pulse from this unit is of constant amplitude and reliable frequency.

The output of the trigger circuit is differentiated and applied to the grid of the output tubes (T_9 to T_{12}). Two crater tubes are connected in parallel to the plate circuit of each of the four output tubes, and thus the circuit is capable of driving eight crater tubes.

This circuit produces very satisfactory timing marks. For example, 5 kc/sec timing marks were produced on Fluorographic film moving at a speed of about 3.6 msec/in. (0.142 msec/mm) which could each be measured, by the use of an optical comparator, to better than 0.003 mm, that is, 0.4 microseconds. The rotating-drum camera shown in Figs. 20 and 21 Chap. 8, was used for these tests. It is somewhat more difficult to obtain sufficient intensity on Fluorographic film than on Super XX.

(iii) Timer for high-speed motion picture camera. The film speed of the Eastman High-Speed Camera Model III is calibrated by photographing the light flashes from a neon-lamp, mounted inside the camera, which is modulated by the circuit shown schematically in Fig. 30. The timing frequencies provided are 1000 and 500 cps.

The stages from T_1 to T_6 are identical in operation to the similar stages in Fig. 28 above. The differentiated timing signals, at either 1000 or 500 cps, are applied to the flip-flop circuit (T_7 and T_8) which drives the output tube T_9. The neon bulb is connected to the cathode circuit of T_9. The output of T_8 is a positive pulse of about 70 μsec duration, one pulse occurring for every cycle of the synchronizing signal. The neon bulb operates satisfactorily when cables as long as 1000 ft are used between the timer and the bulb; this is the greatest length of cable which has been employed. The current in the neon bulb is adjusted by the potentiometer in the cathode circuit of T_9 in order to control the intensity of the bulb; about 5 ma is used at 1000 cps and 3 ma at 500 cps.

This circuit can be used with an external power supply operating from a power line and delivering 300 to 500 v at 40 ma, in addition to current for tube heaters, or from a 6-v storage battery if other power is not available. It is desirable to use a different source of power for operating the circuit than that used for operating the camera because, when the camera starts, a very large surge is introduced which may affect the operation of the electronic circuit, particularly if the power is obtained from a small generator. A Mallory Type VP-552 vibrapack and a filter section are built into the unit for operation from a 6-v battery and a Mallory Type 107 battery charger is included for charging the storage battery from a power line. The 1000 cps tuning fork, the vibrapack and the battery charger are included in a portable wooden carrying case which houses the electronic circuit.

The operation of this unit has been quite satisfactory. When the camera is running at 3000 frames/sec (16-mm film is used in the camera) this circuit produces a timing mark every third frame. By the use of an optical comparator, the distance between two adjacent marks under these conditions can be determined to 0.1 percent, that is, to 1 μsec.

Chapter 10

CONTROL EQUIPMENT

The purpose of control equipment is to simplify, as much as possible, the operation of the blast-measuring equipment. Control equipment serves not only to increase the efficiency and speed of operation but also to reduce to a minimum the possibilities of human errors. In designing control equipment a compromise must be made between, on the one hand, simplicity and maximum efficiency, and, on the other hand, the versatility of the apparatus.

10.1. General description of the control equipment

Three distinct types of operation are involved in the routine measurement of blast waves: the recording of the pressure-time curve, the calibration of the equipment, and routine operational testing and adjustment. The control equipment employed in the Mobile Laboratory for selecting the operations to be performed is described in the following. Similar operation, with slightly different switching circuits, is obtained in equipment, not described here, which is used with the DuMont type 208 cathode-ray oscillograph.

(a) Presetting of equipment in the Mobile Laboratory. — Before the blast wave is measured a number of settings have to be made; once these are made the operation of the apparatus is almost completely determined by the control equipment.

After arranging the gauges and cables, and associating recording channels with each gauge, it is necessary to set the gain of each amplifier. This is done by adjusting the gain to give the correct deflection when a charge-calibration step is applied to the cable. The charge-calibration circuit develops approximately the same charge as is expected to be developed by the gauge [see Sec. 9.2(c)]. The output voltage of the amplifiers is adjusted, by means of the centering control, to be below the center of the cathode-ray tube screen by an amount equal to one-half the expected gauge signal (usually 1 to 2 in.). This is done in order to center the deflection on the tube.

The cable terminations, standard condensers and standard voltage are selected. The step-generator [see Sec. 10.2(c)] delay and duration are set.

The camera speeds are adjusted and the synchronizing signal connected. The beam-brightener durations are adjusted in the two different beam-brighteners, one of which is used for each set of four recording channels. The intensity and focus on the cathode-ray tubes are set.

After these settings have been made, the correct arrangement of equipment is determined by the operation selected on a master operations switch in the master control. For a given position of this operations switch a pilot light indicates that all the equipment is properly set for recording, provided only that the proper presetting of the amplifiers, beam-brighteners, and so forth, has been made.

(b) Sequence of operations. — The operations switch has five positions: position (0), off; position (1), charge calibration step 1; position (2), charge calibration step 2; position (3), recording of the blast wave (shot position); position (4), charge calibration step 3. The calibration steps and the shot are recorded in the order indicated. The first two calibration steps are identical except that the traces on the cathode-ray tube of the two steps are slightly displaced from each other in order to prevent overlapping. The duration of the beam-brightening signal on these steps is just sufficient to provide an adequate trace length for measurement; the length of these traces is kept to a minimum to eliminate unnecessary lines on the records. The third calibration step is similar to the first two except that it is primarily intended to indicate the over-all time constant of the recording equipment [see Sec. 9.2(c)]. Thus as long a beam-brightening duration as possible is used; namely a duration lasting for one drum revolution. This step is also displaced from the other traces.

The beam-brightener duration in the shot position is usually made equal to the time of one drum revolution and the trace of the shot is displaced from the other traces. A timing calibration is obtained from the 3-in. cathode-ray tubes at the same time the recording of the shot is made, so that all the cathode-ray-tube beams are brightened for the recording.

In the "off" position the operations switch turns off the calibration batteries, which are the sources of the standard voltage, and turns off the batteries used to supply the 6-v power to the oscillator and to the control relays. The operations switch also turns off the cathode-ray-tube spots and the camera motor.

When the pilot light on the master control corresponding to a given operation is on, the camera drums are rotating, and to obtain a record it is only necessary to open the camera shutters and either to fire the charge or to actuate the step-generator.

(c) Connections between component parts of equipment during recording. —

(i) Connections for recording the blast wave. The gauge signal is transmitted over cables to the junction box. The junction box contains the high-frequency cable termination. From this unit the signal is connected to the amplifiers by patch cords and from the amplifiers the signal is connected to the cathode-ray tubes. Displacement of the traces on the cathode-ray tubes is provided by relays in the amplifiers which are controlled by the operations switch in the master control.

The synchronizing signal, which is derived from a tripper, or a circuit connected to the firing relay, is first led to the master control, where a meter indicates whether or not the tripping circuit is continuous. Two separate tripping circuits can be connected to the master control, and from the master control to the beam-brighteners. One of these beam-brighteners is used with the 4 5-in. and the 2 3-in. cathode-ray tubes photographed by the drums on one shaft in the rotating-drum camera, and the other beam-brightener is used with the tubes photographed by the drums on the other shaft. The timing tube used for calibrating a drum is brightened at the same time that the recording tubes are photographed by that drum. The timing signal is generated in the timing unit and the oscillator in the timing unit is connected to the 6-v master control DC supply.

(ii) Connections for calibration. The standard condensers and voltage dividers used in the calibration of the amplitude sensitivity are in the junction box. A relay in the junction box, known as the calibration-shot relay, serves to connect the standard condensers to the voltage dividers during the calibration. When the shot is being recorded the standard condensers are connected to ground by this relay, which is controlled by the operations switch. The 1.5-v calibration batteries and the relays which generate the steps are in the step-generator and are connected to the dividers by patch cords. The trip pulse from the step-generator connects to the master control and from the master control to the beam-brighteners. The 3-in. tubes used for the timing calibration are not brightened when the calibration steps are applied. The duration of the beam brightening for the first two calibration steps, which is usually shorter than the duration used for recording the pressure-time curve and the last calibration step, is determined by a selector switch in each beam-brightener. A relay in the beam-brightener, controlled by the operations switch, selects between the step duration and the shot duration.

(iii) Routine testing and adjustment of equipment. — The general operation of the recording equipment can be readily tested by the auxiliary apparatus included in the Mobile Laboratory. The sweep-generator is used only for this purpose: it can be connected to the cathode-ray tubes in order to provide either continuous or single sweeps for observing the output of the amplifiers. The beams of all the cathode-ray tubes may be turned on to the same intensity that is supplied by the brighteners by means of a switch (beams-on switch) in the master control. The beams are turned on for observing the cathode-ray-tube spots while testing and for adjusting the intensity and focus.

The leakage resistance of the gauge circuit may be tested with a resistance-tester built into the control equipment. The resistance-tester is connected directly across the gauge cable by the channel-selector switch in the junction box and either conductor of a balanced cable is selected by the pin-selector switch in the resistance-tester. The continuity of the gauge cables may also be measured by a low-ohms tester built into the resistance-tester.

The voltage of the calibration batteries may be measured directly by an electronic potentiometer which uses part of the resistance-tester circuit. The batteries are connected to the potentiometer by the resistance-tester-potentiometer switch in the resistance-tester-potentiometer.

The output voltage from each step on the voltage dividers may be measured with an external potentiometer by connecting the potentiometer to a plug on the junction box. The channel on which the voltage measurement is made is selected by the channel-selector switch.

10.2. Circuits of the control equipment

(a) Master control used in Mobile Laboratory. -- Figure 31 is the schematic circuit of the master control used in the Mobile Laboratory. The master control contains the master-control or operations switch (switch 1), the beams-on switch (switch 2), the camera-motor switch (switch 3), and the junction-box-heater switch (switch 4).

The master-control switch performs the following operations:

(1) turns the calibration batteries on and off (sections A and B);

(2) turns on, in the shot position, the calibration-shot relay in the junction box (section C);

(3) turns the timing relay in the beam-brightener on in the shot position (section C);

(4) controls the amplifier-displacement relays (sections D and E);

(5) changes the beam-brightener duration from the durations used for recording the calibration steps to that used for recording the shot (section D);

(6) turns on the master control 6-v DC which supplies power for the relays and the tuning fork in the timing unit (section F);

(7) connects the beam-brighteners to either the trip output of the step-generator or to the shot-synchronizing circuit (sections G-J);

(8) turns on the operation lights (section K);

(9) turns off the cathode-ray tube-beams (section L).

The jumper terminals in the tripping circuit are used when two tripping devices are employed in series. The continuity meter indicates when the tripping circuit is continuous.

When the pilot lights on the master-control switch are out, one of the other switches in the control circuit is incorrectly set for recording. When a switch is improperly set, a pilot light adjacent to it lights up. Those switches which are always intended to be in a definite position during the recording are connected into the master-control pilot-light circuit.

The beams-on switch turns the beams of all cathode-ray tubes on for testing. It is wired into the master-control pilot-light circuit; during recording it is turned off.

The camera-motor switch turns on the motor which drives the rotating-drum camera. Also, to prevent 60 cps pickup from the charger, it turns off the charger in the 6-v master-control DC circuit. All these circuits are controlled by relays. This switch is wired into the master-control pilot-light circuit.

The junction-box-heater switch actuates a relay which turns on heaters used to evaporate moisture in the high-impedance section of the junction box. The switch is turned off during the recording to prevent 60 cps pickup and is wired into the master-control pilot-light circuit.

The relays used in all circuits near high-impedance lines or near circuits sensitive to trip pulses are shunted by small resistors placed directly across the coils. When a relay is closed or opened, a large-amplitude transient signal is generated by the inductance of the coil. This signal is shunted out by the low impedance of the battery when the relay is energized, but unless a shunt is specially connected across the coil, it is not shunted out when the relay is opened.

The master control is built on a 7-in. panel without a chassis. All wiring is enclosed and all connections are made at the back of the unit.

(b) Junction box used in Mobile Laboratory. -- The schematic circuit of the junction box used in the Mobile Laboratory is shown in Fig. 32. The fundamental purpose of the junction box is to provide the circuits for the calibration of the amplitude sensitivity of the recording equipment and to provide the networks for the high-frequency termination of the gauge cables. The junction box also contains provisions for the connection of circuits for the measurement of the short- and open-circuit resistance of the gauge cables and for the measurement of the voltage output of the voltage dividers.

The gauge signal on each channel is connected to the junction box by two unbalanced cables which, together, provide a balanced system. The input plugs are connected to plug-in standard condenser and cable-compensating units shown in the figure. These units contain jacks for standard condensers, padding condensers, and terminating resistances and inductances (see Sec. 4.3). The standard condensers are used both as standard condensers for the application of a charge calibration step and as padding condensers for cable-termination. These units plug into a lucite strip which in turn can be plugged into jacks in the junction box. Since the compensating units may be inserted in the jacks in the junction box corresponding to any channel, it is possible to associate a compensating unit with one cable and thus when cables are changed no adjustments have to be made to obtain the correct termination.

The output of the compensating unit connects to the V-Q switches (switches 9 and 10). These switches determine whether the equipment is to be connected for push-pull or single-ended operation and also connect the amplifiers to the voltage dividers to permit the use of push-pull or single-ended voltage steps. For ordinary push-pull operation the V-Q switch is in the position shown in the figure (PP-Q), and the output of the compensating unit is attached to the plug which connects to the amplifiers. In the third position (SE-Q) pin 1 of the amplifiers is grounded and pin 2 is connected to the compensating unit. In the second position (PP-V) the amplifiers are directly connected to the voltage dividers, and in the fourth position (SE-V) pin 2 of the amplifiers is connected to the voltage dividers and pin 1 is grounded. The direct connection of the amplifiers to the voltage dividers is used when it is desired to test the amplifier response by means of a voltage step. By the use of a voltage step the response of the amplifiers can be determined without being affected by the cable response, and the cables are disconnected from the circuit to minimize the rise time of the step [see Sec. 9.2(q)]. One section (9A or 10A) of the V-Q switch connects the voltage divider for either push-pull or single-ended operation, as described below. A pair of switch sections similar to 9H and 9I are used for each channel. The sections for channels 1 to 4 are ganged on switch 9 and the sections for channels 5 to 8 are ganged on switch 10 (only section 9H and 9I are shown in the figure). The switch sections of the V-Q switches, which are in the high-impedance part of the circuit, are made of steatite or lucite to reduce leakage. The V-Q switches are connected to the master-control pilot-light circuit; during the recording they may be set for either push-pull or single-ended operation.

The low side of the standard condensers connects to the calibration-shot relay. When the operations switch in the master control is set to the shot position, these relays are energized, and the standard condensers are grounded. When the operations switch is in any of the calibration positions, the calibration-shot relay is de-energized and the standard condensers are connected to the voltage dividers. These relays, one of which is used for four channels, are Automatic Electric Series AQA with 9 form C (break-make) contacts.

Two voltage dividers are employed, one for each set of four channels. These voltage dividers, which are connected to 1.5-v batteries in the step-generators described in Sec. 10.2(c), contain two identical sets of 22 precision resistors each, which are connected between ground and the battery. When the equipment is connected for push-pull operation, the output voltage is taken from both halves of the divider and can be varied from 1 to 1443 mv in 5-db steps. An individual four-gang 11-position selector switch selects the voltage step on each channel and an individual toggle switch selects either the high or low range on the output of the selector switch. The outputs of the toggle switches connect to the V-Q switch and the calibration-shot relay. When the amplifiers are used in single-ended operation, one half of the voltage divider is shorted to ground to eliminate pickup from the step-generating relay, as described in the next part of this section. A shunt resistor is connected across the divider when the V-Q switch is set to single-ended operation in order to maintain the battery drain at 1 ma. The over-all divider and switching circuit is shown schematically in Fig. 33.

The channel-selector switch (switch 8) is used to connect a channel on which resistance measurements are to be made to the resistance-tester, which is described in Sec. 10.2(d). This switch also connects the toggle switch output of the voltage divider for each channel to a plug on the rear of the junction box. An external potentiometer can be connected to this plug for measuring the output voltage of each step on each channel of the dividers. The channel selector switch is connected into the master-control pilot-light circuit. Its correct position during recording is the position shown on the circuit.

As indicated on the circuit, considerable care is taken in making ground connections to eliminate ground loops. No circuit grounds are connected to the chassis.

The junction box is built on a 28-in. rack panel. The jacks for the compensating units are mounted on a lucite panel along the bottom of the junction box. The bottom part of the unit, which houses the compensating units, is 21½ in. deep and rests on the bottom of the relay rack. The gauge cables are plugged in at the bottom rear of the unit and the other connections are made at the top. Two 150-w bulbs are included for heating the box in order to remove moisture from the high-impedance connections. The unit is completely enclosed.

(c) Step-generator used in Mobile Laboratory. — The circuit used in the Mobile Laboratory for generating calibration steps is shown schematically in Fig. 33. When the trip switch is actuated this circuit develops a synchronizing pulse to trip the beam-brightener or sweep-generator and, after a predetermined and adjustable interval, breaks the circuit of the voltage divider to apply a step.

The circuit is initiated by depressing either the micro-switch S_2 or a similar switch located at a distance from the unit and plugged into the remote trip terminals. When this switch is depressed a pulse is applied from the cathode of the cathode follower T_1 to trip the beam-brightener or sweep-generator and to trip the flip-flop time-delay stage (T_2 and T_3) in the step-generator. When the flip-flop time-delay resets, a signal is applied to the second flip-flop circuit (T_4 and T_5). The initial pulse from T_4 applies a signal to cathode followers T_6 and T_7 which de-energizes the relays in the voltage-divider circuit and thus produces a step.

The reset time of the first flip-flop circuit (T_2 and T_3) determines the delay between the initiation of the beam-brightener and the step. (This delay is limited to a minimum of about 100 μsec by the delay in the relay.) The time delay is continuously adjustable from about 5 to 500 msec and is controlled by switch S_3, which selects the condensers in the circuit, and by potentiometer R_1. The delay has been found to be reproducible to 2 percent or better from shot to shot. The duration of the step, that is, the time between the initial de-energizing of the relay and the re-energizing when the circuit is returned to its original condition, is determined by the second flip-flop circuit. It can be set at either 500 or 2000 msec duration by switch S_1.

Two relays are used, one for each of the two calibration batteries and voltage dividers in the junction box. The complete voltage-divider circuit is shown schematically in Fig. 33. A polarity switch is included in this circuit to change the polarity of the step. This is used when different polarity gauges are used and to enable the step to deflect in the same direction as the pressure wave. The currents in the relays are adjusted by potentiometers R_2 to the minimum value which will reliably close the relay. If too large a current is used the relay will bounce when it opens. Under the conditions of minimum current, fairly chatter-free steps can usually be obtained, although it is necessary to select relays. The opening time of the relay is not very rapid and causes a slight rounding at the initial break of the step which is noticeable on film speeds in excess of 3 msec/in. At these speeds chatter on the rise-line of the step can also be observed. These step-generators have been used for providing calibration steps at film speeds as high as 1.5 msec/in., but the step output contains too large an amount of chatter to be reliably used for testing the high-frequency response of the recording equipment at these speeds. The step-generator described in Ref. 33 is more satisfactory for high-frequency testing than the relay type step-generators, although the former does not produce a push-pull step.

An inductive signal generated in the relay coil produces a spurious signal across the relay contacts just before they are opened. The signal is not usually noticeable on push-pull steps, but one side of the relay coil and one of the relay contacts must be grounded to eliminate it on single-ended steps. The grounding of the relay contacts for single-ended operation is brought about by the V-Q switch in the junction box.

Pulsed tripping of the step-generator can be obtained from a neon-bulb relaxation-oscillator T_3. The pulsed tripping is used for testing. The pulses from the relaxation oscillator are connected to T_1 by switch SW-6, which is also connected into the master-control pilot-light circuit. The rate of pulsing is slightly less than the interval that is necessary between successive trips of the beam-brightener [see Sec. 6.5(b)]. Two pulsing rates can be used; they are selected by the switch which determines the duration of the step, S_1.

The step-generator is built in the same chassis and operates from the same power supply as the resistance-tester and potentiometer described in the following. This circuit has been reliable and, within the limitations indicated above, has given satisfactory operation. Occasionally transient parasitic oscillations in the remote trip circuit have affected the time delay. This difficulty is usually eliminated by rearrangement of the wiring in the tripping circuit.

(d) Resistance-tester and potentiometer used in Mobile Laboratory. -- The circuit used for measuring the open- and short-circuit resistance in the gauge circuit and the voltage of the calibration batteries is shown schematically in Fig. 34. Two high-resistance ranges provide measurement of resistances from 20 to 10,000 megohms and one low-resistance range provides measurement of resistances from less than 1 ohm to 200 ohms. The potentiometer measures the 1.5-v calibration batteries with an accuracy of about 3/4 percent.

The various operations of the circuit are selected by switch SW-5, the resistance-tester-potentiometer switch. This switch connects the same meter into the circuit for all operations, connects the calibration batteries to the potentiometer, and connects the resistance-tester to the pin-selector switch SW-7. The pin-selector switch is used to select the particular pin of a balanced cable on which resistance measurements are to be made. It connects to the channel-selector switch in the junction box.

The high ranges of the resistance-tester operate by measuring the voltage across the unknown resistance in a voltage divider containing a known resistance. A voltage of 45 v is applied to this divider, and a 10-megohm or a 2-megohm resister, depending on the range, is used in series with the unknown resistance. The voltage is applied to the grid of a cathode follower T_3 and a 200-μa meter is connected between the cathode of this tube and a tap on the cathode circuit of another cathode follower T_4. The meter is adjusted by the potentiometer R_2 connected to the grid of T_4. A diode T_2 is connected across the input-resistance divider to protect the meter when a small resistance is connected to the grid of T_3. Potentiometer R_3 is used to adjust the lowest voltage to which the grid of T_3 can be placed without damaging the meter, so that R_3 serves as a meter adjustment when the input is shorted and R_2 adjusts the meter when the input is open-circuited. The grid of T_3 connects to the pin-selector switch SW-7 through the resistance-tester-potentiometer switch. This circuit has operated satisfactorily. Its only particular advantage over conventional ohmmeters is that the scale of the high-resistance ranges is expanded more than in the latter.

The low-ohms section of the resistance-tester is a conventional ohmmeter circuit. A 3-v battery is used as a source of voltage and the same 200-μa meter which is employed for testing high resistances is used. Potentiometer R_1 adjusts the meter zero in this circuit. The input of the low-ohms tester is connected to the pin-selector switch through the resistance-tester-potentiometer switch.

The potentiometer is, in principle, similar to a standard Poggendorf potentiometer with an electronic detector in place of a galvanometer. The calibration battery to be measured serves as a working battery to supply one milliampere to a precision resistance divider and thus the battery is measured when approximately the same current is being drawn from it as when it is used to supply a voltage divider. The electronic circuit, which uses the same meter circuit as that used in the resistance-tester, contains a DC amplifier T_1 that is connected to the grid of T_3. The electronic circuit is used only as a null detector. Potentiometer R_4 is used to adjust the grid bias of T_1 to obtain minimum grid current, and potentiometer R_5 adjusts the voltage on the output of the divider, which is connected to the plate of T_1, to the same value that is applied to T_3 by the resistance-tester circuit. Potentiometer R_2 is used to adjust the meter. The grid-current adjustment depends on the heater voltage of T_1 and this voltage should be regulated, although regulation has not been used in the present circuit. The calibration-battery voltage can be read to 5 mv, or 0.3 percent, and the accuracy of the measurement is about 3/4 percent when the line voltage, and therefore the heater voltage, is within 3 to 4 percent of the voltage at which the grid current was adjusted. Except for the effect of heater voltage on grid current, this circuit has been satisfactory. It would probably be simpler and more reliable, however, to use a galvanometer, such as the Rubicon Cat. No. 3002-sys, instead of the electronic detector.

The resistance-tester and potentiometer is included in the same chassis as the step-generator. A standard 8-3/4 in. rack panel and a 17X13X3-in. chassis are used. All connections are made to plugs at the rear of the chassis and the circuit grounds are insulated from the chassis. The plate power is obtained from the master-control power supply [see Sec. 11.2(c)].

Chapter 11

POWER SUPPLY

Electric power is used for the plate supply and heaters of all electronic equipment, for operating motors, tools and lights, for heating, and for communications. The primary sources of electric power are generators, power mains, and batteries.

At this laboratory plate supply power is obtained from either rectified and filtered AC or from dry batteries. Although dry batteries provide stable voltages, they are in general impractical for the operation of equipment drawing high currents or requiring high voltages. On the other hand, although sufficient current and voltage can be obtained from AC power sources, these sources are much less stable than dry batteries. Instability in the plate voltage of high-gain amplifiers and of other circuits used in blast-measuring equipment must be much less than that tolerated in conventional electronic equipment, and thus it is usually necessary to regulate either the AC voltage or the plate supply voltage. Although the plate-supply voltages are the most critical, in high-gain and direct-coupled circuits stable heater voltages, and sometimes DC heater voltages, are required.

This chapter will be concerned with the requirements of the power used in blast-measuring equipment, with the characteristics of the primary sources of power, and with the use of electronically regulated power supplies.

11.1. Power requirements

(a) Power for electronic equipment. —

(i) Plate supply power. A different degree of regulation and stability is required in the power supplies used for the different components of the electronic equipment employed in blast measurements. Power supplies may be divided into three groups: (1) those used for amplifiers, (2) those used for control equipment, such as beam-brighteners and oscillators, and (3) those used for cathode-ray tubes.

(1) Amplifier power supplies. The low-level stages of amplifiers require power supplies with very little ripple and instability, and deviations of the output voltage from a perfectly steady, unvarying, DC voltage are sometimes required to be less than a few millivolts. In air-blast equipment for measuring the pressure waves from large charges it is not, in general, possible to use decoupling filters in low-level stages for the purpose of removing the effects of ripple and instability in the power supply. Decoupling filters cannot be used because they introduce a finite time constant which reduces the low-frequency response of the amplifier. Consequently power supplies with a very small amount of ripple and instability are necessary to supply the low-level stages of high-gain amplifiers, and frequently push-pull circuits must be used to reduce the effect of these spurious signals.

It is usually necessary for the plate-supply voltage to be independent of the ordinarily encountered line-voltage fluctuations and the drift in output voltage should be small. The internal resistance of the supply should be sufficiently low to prevent coupling between stages of the amplifier, or between different amplifier channels. (The operation of more than one amplifier from one power supply is usually the most efficient arrangement.)

The quantitative requirements which must be met by power supplies for use with high-gain amplifiers are best indicated by the characteristics of the power supplies used at this laboratory. These power supplies are adequate for the operation of the amplifiers in the Mobile Laboratory, but the ripple level limits the gain which can be used in preamplifiers employed with oscillographs [see Sec. 5.3(a)]. The total peak-to-peak ripple voltage of these supplies, including all line-frequency harmonics, is usually below 0.0005 percent in that part of the supply used to deliver positive voltages, and below 0.002 percent in that part of the supply used to deliver negative voltages. The total instability of all sorts is usually less than 0.002 percent. A 5 percent change in the line voltage changes the output voltage of the power supplies by about 0.001 percent, or less. The drift, over a day's operation, of the power supplies used at this laboratory is less than that which can be observed on a voltmeter used to measure the entire output voltage of the supply, and over a period of several months the change in output voltage is generally less than 0.5 percent.

(2) Power supplies for control equipment. The over-all requirements of stability and ripple in power supplies for control equipment are much less stringent than in amplifier power supplies. Any circuit involving trigger circuits is intrinsically sensitive to pulses, so that line-voltage surges and pulses from other circuits or stages must not be transmitted through the power supply. Thus these power supplies should have a sufficiently low internal resistance not to cause coupling between stages of the control equipment, particularly when more than one unit is used with a single power supply. The power supply must be relatively free from drift if direct-coupled stages are used in the control circuits.

(3) Cathode-ray-tube power supplies. Cathode-ray tubes usually require negative voltages of from 1000 to 5000 v and, if intensifier-type tubes are used, positive voltages of the same magnitude are also necessary. The current drain is less than a milliampere per tube, although as much as 1 ma may be used in the dividers employed to supply voltages to the control electrodes of the tube. Since the deflection sensitivity of a cathode-ray tube is inversely proportional to the accelerating anode voltage and depends to a smaller extent on the intensifier voltage, variations in the supply voltage have a direct effect on the sensitivity of the tube. It is believed that, in certain cases, lack of reproducibility of the sensitivity of the recording equipment was due in large part to fluctuations in cathode-ray tube supply voltages introduced by line-voltage variations. Thus cathode-ray tube power supplies, particularly those used to supply the accelerating voltage, should be independent of line-voltage fluctuations.

The ripple level in a cathode-ray tube supply is not very critical but if too much ripple is present intensity modulation will result.

The impedance of the supply and of the resistance dividers must be sufficiently low to prevent coupling between the intensity modulation and accelerating voltages on a single tube or between tubes operated from the same dividers or power supplies.

(ii) Power for tube heaters. Since there is a thermal lag between the change in the emission of a heater-type tube and the change in heater voltage, heater-type tubes do not respond to rapid voltage fluctuations, provided that the long-time average voltage remains constant. Most of the equipment used in blast measurements has been operated from gasoline-driven generators, the mean output voltage of which is controlled within a few percent, so that the rapid variations which occur in the output voltage from the generator do not affect the tube heaters. When the mean line voltage is likely to change over long periods of time, however, as when power mains are used, control of heater voltages, particularly in high-gain direct-coupled circuits, may be necessary.

Alternating-current heater supply is used in most circuits, but the low-level stages of amplifiers, particularly those with large grid resistors, pick up considerable ripple when operated from AC heaters. Consequently DC heaters are always used for low-level amplifier stages. The DC heater supply must be grounded at some point to prevent it from picking up stray signals.

(iii) Power for auxiliary control equipment. Many of the control and switching circuits used in blast-measuring equipment are located near low-level, high-impedance circuits. Under these circumstances, in order to prevent pickup, 6-v DC relays are used rather than AC relays.

(b) Power for working equipment. — In addition to the power required for the electronic equipment, power is of course required for lights, fans, intercommunication systems, tools, water pumps, heaters for photographic solutions, and so forth. The most convenient type of power for these applications is probably 115-v, single-phase, 60 cps.

(c) Interaction between the power supply and recording equipment. — Electric and magnetic fields are easily picked up by the gauge cables, high-gain amplifiers, and cathode-ray tubes. It is usually possible, by proper shielding, to eliminate the effects of spurious electric fields from the electronic equipment, but it is more difficult to remove the effects of magnetic fields. It has been found necessary, in order to eliminate pickup from magnetic fields, to remove all transformers and high-current power lines from the neighborhood of the cables, amplifiers and cathode-ray tubes. Generators and power lines are kept as far away as possible from gauge cables in the field and push-pull cables are employed to cancel out pickup. Care must be taken to eliminate ground loops, both resistive and capacitive, in the gauge cables, power supplies, generators, power mains, and heater supply circuits. The location of the test site should be as far as possible from high-tension power lines.

Intermittent loads on the power source may interact with the recording equipment. This is particularly troublesome when equipment other than that used for blast measurements is connected to the same source of power, as, for example, when power-company mains are used. Motors in oscillograph cameras and sequence devices, and in motion-picture cameras used to photograph the explosion, may be sources of large intermittent loads. The Eastman high-speed camera, for example, draws 30-amp starting current. When the loads are connected to the same power sources used to supply the recording equipment, and are turned on immediately before the blast wave is to be recorded, large surge currents may be introduced, and it is usually necessary to supply such loads from a source of power independent of the blast-measuring equipment to prevent interaction with the latter.

11.2. Primary sources of power; power control

The sources of 115-v AC power used at this laboratory are: power mains, generators, and rotary converters. AC power is employed for operating plate-supply power supplies, tube heaters, and working equipment. The sources of high-current DC power are storage batteries. At low voltages, storage batteries are used for tube heaters and control relays, and at higher voltages for supplying rotary converters. Dry batteries are sometimes used as a source of bias and of well-regulated, low-current plate supply.

(a) Sources of AC power. -- All the AC power used at this laboratory has been single-phase, 115-v, 60 cps. The control and regulation of AC power is discussed in part (c) of this section.

(i) Commercial power lines. The voltage regulation of most commercial power lines is poor. Since the voltage is affected by the loads applied by a large number of consumers, it is not uncommon to find rapid voltage fluctuations of 5 v and a change in voltage during the day of as much as 10 v. The frequency stability and load regulation of commercial power is, of course, much better than that which can be obtained from generators or rotary converters. Commercial power lines are not usually available, however, at the test sites used for blast measurements.

(ii) Gasoline generators. Since the stability of the voltage developed by a generator at constant load depends primarily on the speed of rotation of the generator armature, very rapid fluctuations in voltage are prevented by the inertia of the armature and of the gasoline engine. The best generators which have been used at this laboratory show voltage fluctuations of about 1 percent when the voltage is measured on a short-period voltmeter, but other types of generators that have been used are not as stable as this. To obtain the best stability from any generator it is essential to use clean, dry and well-filtered gasoline, and the generator must be kept in good condition.

The load regulation of a generator depends on the mechanical speed governor on the gasoline engine. This governor usually takes a second or more to respond, and it does not completely compensate for changes in load.

Since the frequency depends on the generator speed, the frequency stability of a small generator with the usual type of governor is not comparable to the frequency stability of the current in a commercial power line.

The most satisfactory generators which have been used at this laboratory are the Model V-45S-10 made by D. W. Onan and Sons. These are 5-kw, 115-v, 60 cps, single-phase generators with a four cylinder water-cooled engine which has a normal rotational speed of 1800 rpm. The generator has a self-starter operated from a 12-v storage battery which may also be used as a generator to deliver 150 w at 12 v DC. This DC generator is used to supply heater current for the tubes in the high-gain amplifiers. A similar 3-kw unit made by Onan has also been used satisfactorily, but considerable difficulty was experienced in using the Onan Model OTC-44 2-kw air-cooled units.

Since most generator chassis are connected to one side of the AC output, it may be necessary to insulate the generator from ground in order to prevent ground loops. When high-gain systems are used, generators are ordinarily located about 50 ft from the recording equipment and the gauge cables in order to reduce pickup, and the generators are always provided with electrostatic shielding.

(iii) Rotary converters. Rotary converters transform direct current into alternating current. At constant load the output voltage from a converter is ordinarily as stable as the source of DC voltage, but the load regulation is very poor. Extreme care must be taken when switching loads on a small converter to prevent the voltage from rising to very high values. Hash is sometimes produced by brush arcing on the DC commutator of a converter and is often a serious source of pickup on high-gain amplifiers.

The converters used at this laboratory have been 400- and 600-w types made by the Janette Manufacturing Company. Twenty heavy-duty automobile storage batteries of 100 to 120 amp-hr capacity are used to supply 129 v for operating the converters. These batteries are charged by a rectifier operating on 115-v AC, such as the General Electric Model 6RB10Y5 which charges at 6 amp. Fluctuations in the AC voltage from which the charger is operated introduce variations in the DC battery voltage. The extent to which these AC voltage fluctuations affect the DC voltage is determined by the internal impedance of the batteries and the ratio of the charging current to the load current. Usually the charging rate must be lower than the rate of discharge, so that the batteries run down while in use.

Although rotary converters operated from storage batteries provide a more stable AC voltage than that provided by power mains or generators, converters are not a convenient source of power. Approximately 1000 lb of batteries, a converter, and a large battery charger (weighing about 80 lb) are required. In addition, AC power for the battery charger is needed. This quantity of equipment is not sufficient for much more than 1 kw of power.

(b) Sources of low-voltage DC power. -- Low voltage DC power is used for operating tube heaters and control relays in circuits in which AC would introduce pickup.

(i) DC power for tube heaters. Direct-current power for 6-v tube heaters is usually obtained from automobile storage batteries. Ordinarily it is most convenient to locate the batteries at some distance from the electronic circuits, and thus line resistance has an appreciable effect on the voltage developed at the tube sockets. The DC heater supply circuits [see part (c) of this section] employed at this laboratory use 8 to 12 v and a series rheostat to serve as a dropping resistor. An ammeter is included in the circuit so that exact adjustment of the heater current can be made.

The heater-supply batteries are charged continuously during operation from battery chargers operating on the 115-v line or from the DC windings of the Onan generators. Usually no difficulty is encountered from ripple or instabilities even when the charging rate is equal to or greater than the rate of discharge. Fifteen amperes have been drawn from 6-v batteries in series when charged from the Onan generators, but this is not necessarily an upper limit. The battery chargers which have been used are: (1) Mallory Type 107, which delivers 6 amp to a 6-v battery, but can also be used on an 8-v battery. (2) General Electric Type 6RB19Y2 which charges at 6 or 12 amp at 12 v. These battery chargers contain isolating transformers; battery chargers with auto-transformers are generally unsatisfactory because they can easily be shorted out and may introduce ground loops.

(ii) DC power for control relays. DC power for operating control relays is usually obtained from Willard CR-2-3 low-drain storage batteries. These are charged continuously during operation from Mallory Type 3C battery chargers that operate from the 115-v AC source. The charging circuit is connected to the master control [see Sec. 10.2(a)] which, in order to eliminate pickup, turns off the charger while the recording is being made. In some cases it is necessary to use an 8-v battery to compensate for line drop. (See Fig. 35.)

(c) Power-control circuits. -- To obtain reliable blast measurements it is usually advisable to control accurately the voltage of the power source. When regulated plate and heater supplies are used, the control of the AC voltage is not critical, but generally, except when the heaters are operated from DC, heater regulation is not provided, and consequently it is necessary to control the mean AC voltage even when plate-supply regulation is employed.

(i) Power-control circuit used in the Mobile Laboratory. The power-control circuit in the Mobile Laboratory, shown schematically in Fig. 35, is typical of the control circuits used at this laboratory. The layout of the switchboard panels for this circuit is shown in Fig. 40.

Both AC and DC power are obtained from an Onan V-45S-10 generator. The primary voltmeter should be accurate, have a large scale, and should have a sufficiently short period to indicate short-time line-voltage fluctuations.

Meters with a copper-oxide rectifier are not sufficiently reliable for this application. The Westinghouse meter used, which is hand-calibrated, has been very satisfactory. Voltage is controlled by a variac.

The instrument power supplies are turned on by one switch and a time-delay relay is included to apply current to the heaters before the plate supplies are turned on. Heater transformers for the control equipment, cathode-ray tubes, and the output stages of the amplifiers, are included in the beam-brightener power supply. A varitran auto-transformer in the primary circuit of the heater transformers is used to boost their output voltage in order to compensate for line loss between the transformer and the tube sockets.

The DC circuits are similar to those described above.

(ii) Voltage regulators. Voltage regulation of some sort is required to insure reliable operation of the electronic equipment from the usually available sources of power. Cathode-ray tubes, in particular, require voltage-regulated supplies because the deflection sensitivity of a tube depends on its accelerating voltage. Regulation of plate voltages can be obtained by regulating the AC power or by electronic regulation of the plate supplies.

A number of different types of voltage regulating devices are available, but not all of them can be used on both power mains and generators. A constant-voltage device for use with blast-measuring equipment should meet the following requirements: (1) Input voltage fluctuations should be effectively eliminated in a time that is short compared to the time constant of the power-supply filters. (2) The output of the regulator should contain very little wave-form distortion. (3) A regulator for use with generators should be independent of frequency.

Commercially available regulators have not been used to a large extent at this laboratory, primarily because none are entirely satisfactory. A wave-form distortion is present in most regulators, which affects the output voltage of condenser input power-supply filters, and although mechanical regulators do not cause a wave-form distortion, they react too slowly for most purposes. The Superior Electric Company, however, manufactures a special-purpose mechanically-controlled regulator that responds in 0.05 sec. This regulator, which may prove practical, has not been used at UERL.

Regulators made by the Sola Electric Company have been employed for voltage regulation of power mains. These regulators introduce a 7 percent wave-form distortion at full load, but the output is considerably more distorted at light loads. Although the standard regulators made by Sola depend on frequency, a new regulator has been made, which has not been used at this laboratory, that is relatively independent of frequency.

A regulator made by Sorensen and Company does not depend on frequency and has recently been employed successfully for the regulation of a generator used to supply power to equipment used for the study of underwater shock waves.

Generators may be regulated by somewhat different methods. Although all generators contain mechanical governors, which regulate the voltage within about 3 percent, these governors do not respond with sufficient rapidity for the applications at hand. It is possible, however, to use an electronic circuit, which is controlled by the output voltage of the generator, for varying the field current and thus for compensating for voltage fluctuations. A circuit of this type was tried at UERL but it was impractical to regulate the generators in use by this method because they had extremely high field currents. Electro-mechanical regulators are made which respond somewhat more rapidly than the mechanical governors on generators. This type of regulator, however, has not been used at UERL. Regulators of this type are made by the General Electric Company and are called Diactor regulators.

11.3. Regulated power supplies

All equipment employed in air-blast measurements that has been designed recently at this laboratory uses plate supplies with electronic regulation. In some equipment, particularly cathode-ray-tube circuits, a steady voltage supply is necessary to obtain stable sensitivity, and in direct-coupled circuits steady voltages must be maintained to prevent drift. Electronic regulation of plate supplies has, in general, proven to be more practical than regulation of generators or power mains. Regulated power supplies are also advantageous because they have a very low internal impedance, and consequently prevent coupling between stages or units, and, in addition, because they can be used to reduce ripple voltage.

Gaseous voltage regulators, such as VR tubes, are not adequate for the amplifier circuits used at this laboratory.

Two types of regulated supplies have been used. One type, of which a number of essentially similar units have been built, is used to supply positive and negative voltages to amplifiers and control units at voltages up to 350 v from ground. The other type is used for cathode-ray tubes.

(a) Amplifier and control equipment power supplies.* — The schematic circuit of a typical low-voltage power supply and stabilizer is shown in Fig. 36. This stabilizer is used to provide 160 ma at +360 v and -320 v for four of the high-gain amplifiers used in the Mobile Laboratory [see Sec. 5.3(c)]. It consists of a filter and two stabilizers. One stabilizer is used to control the entire output voltage of 680 v and the other is used to stabilize the output around ground. The characteristics of the output of this power supply are described in Sec. 11.1(a).

The main part of the regulator consists essentially of a degenerative-type stabilizer with one pentode amplifier and an unbalanced μ-type amplifier. An S-type connection is used to the screen of the pentode to compensate for input voltage fluctuations [55]. The operation of this part of the stabilizer

*Miscellaneous information on regulated power supplies will be found in Refs. 55 through 59, inclusive.

is as follows (to simplify the explanation of the operation it will be assumed that the power supply is completely stabilized about ground; the supply behaves in essentially the same way if it is fixed relative to ground by the second part of the stabilizer only). When a positive change in output voltage occurs, the cathode of T_7 becomes more positive, which, since the grid is at a relatively fixed potential, increases the negative grid bias. This change in bias increases the voltage at the plate of T_7 and therefore at the grid of T_6, so that the voltage at the plate of T_6 is lowered. Since the three parallel tubes T_3, T_4, T_5 are in series with the load, the decrease in voltage at the plate of T_6, which increases the negative bias on these three tubes and therefore increases their dynamic plate resistance, lowers the output voltage, tending to compensate for the original change in voltage. This action compensates for load changes and changes in the output voltage of the filter, which may be due to either load changes or line-voltage fluctuations. The screen of T_6, which is connected to a divider across the output of the filter, also compensates for changes in the filter voltage. A positive change in the filter voltage increases the screen voltage of T_6, raising its plate current, which, as for a signal on the control grid, raises the resistance of T_3, T_4 and T_5 thus tending to compensate for the change in the filter voltage. Negative changes in voltage on either the output of the stabilizer or the output of the filter are compensated in the same manner as positive changes.

In conventional stabilizers of this type the grid of T_6 is connected to a resistance divider across the output of the stabilizer instead of to the supplementary unbalanced μ-type amplifier. Conventional supplies are usually constructed with the screen of the pentode connected to the output side of the stabilizer rather than to the output of the filter.

By connecting the screen of T_6 to the output of the filter it is possible to balance the circuit so that, for small changes in the filter voltage, no change in output voltage occurs. This circuit makes use of the bridge method for measuring the transconductance of a vacuum tube. Equations for the balance conditions are given in Ref. 55. In practice the condition of balance is obtained by controlling the fraction of the voltage of the filter applied to the screen of T_6, and the stabilizer can be made to overcompensate or undercompensate for input fluctuations by the use of this circuit. Since the balance depends on the transconductance of the screen circuit of T_6, which is not a constant for different values of the plate current, the balance conditions are maintained only for very small changes in filter voltage. The critical nature of the balance conditions is even greater when the control grid of the amplifier tube is connected to the filter output. Consequently this circuit does not provide sufficient compensation for input fluctuations.

Potentiometer R_3 is used for controlling the balance of the screen circuit in Fig. 36. A somewhat more convenient circuit can be employed which does not change the DC voltage of the screen but still permits balancing for changes in voltage. In this circuit one divider is connected across both the output of the filter and the output of the stabilizer. The two ends of a potentiometer are connected to points on each divider which are at the same voltage. This voltage is adjusted to the desired screen potential and the screen is connected to the tap on the potentiometer. Since the stabilizer output is relatively constant, the potentiometer controls the fraction of the change in filter voltage applied to the grid without changing its DC operating potential.

The single pentode amplifier used in conventional stabilizers provides sufficiently good regulation and a low enough internal impedance for most purposes, but even with the screen of the pentode connected to the output of the filter, the balancing of input fluctuations is very critical. The additional amplifier tube T_7 provides much better control of input fluctuations than is obtained with the pentode alone. The function of the screen connection on the output of the filter is less important under these conditions than when a supplementary amplifier is not employed, but the screen connection has a noticeable effect even when the supplementary amplifier is used. Since the adjustment of the screen control is not particularly critical when T_7 is included in the circuit, it is customary, when the circuit is adjusted for line-voltage fluctuations, to replace T_7 by a divider.

The supplementary amplifier T_7 is similar to the circuit used for measuring the amplification factor of a vacuum tube [55]. If the resistance of the VR tubes T_{12} to T_{14} and the 1000-ohm series resistor were equal to μ times the 10,000-ohm resistor in the cathode of T_7, where μ is the amplification factor of T_7, the output voltage at the plate of this stage would follow the B^+ voltage exactly. With the parameters used in this circuit, however, voltage gain is obtained, and the change in output voltage at the plate of T_7 is greater than the change in the B^+ voltage.

The resistance of the VR tubes T_{10} and T_{11} in the cathode of T_6 reduces the gain of this stage by the factor $1/(1 + g_m R)$ where g_m is the transconductance of T_6 and R is the resistance of the two VR tubes in series. The smaller the resistance of the VR tubes T_{12}, T_{13} and T_{14} in the divider connected to the cathode of T_7 relative to the resistance between the cathode and B^-, the greater the fraction of the change in output voltage of the stabilizer applied to the cathode and thus the higher the effective gain of the stage. The VR tubes are operated at a current of 20 ma and are by-passed by condensers. The 1000-ohm resistor in series with the VR tubes in the circuit attached to T_7 is included to prevent oscillation of the VR tubes, which have a negative-resistance characteristic at certain frequencies.

The main part of the stabilizer has a tendency to oscillate. This is prevented by the use of large electrolytic condensers on the output of the stabilizer. Either these condensers or the VR tubes probably introduce some of the hash and instability in the output of the supply, although this hypothesis has not been tested. It has been proposed that if the high-frequency response of T_7 were increased relative to that of T_6 by lowering the plate load resistor of T_6, the oscillations, which are due to phase shift, might be prevented without the use of the electrolytic condensers.

The second part of the stabilizer, consisting essentially of T_8 and T_9, is used to stabilize the output of the supply about ground. It was found necessary to use a very low-impedance device for stabilizing the ground point in order to eliminate 60 cps pickup, and neither VR tubes nor by-passed resistance dividers operating at reasonable currents were adequate. The ground stabilizing circuit is not ordinarily used to supply current, most of the current that is drawn from the supply being between B^+ and B^-. This part of the power supply is a conventional degenerative stabilizer and amplifier. It has proven entirely satisfactory and has been used in over a dozen different supplies for periods of two years or more.

The AC power for the supply shown in Fig. 36 is obtained through a time-delay relay in the power-control panel in the Mobile Laboratory (see Fig. 35). The power supply is built on a 17X13X3-in. chassis with a standard 8 3/4-in. rack panel. Connections are made at the rear of the chassis and only pilot lights and fuses are on the front panel. The circuit grounds are not connected to the chassis.

All the stabilizers used in air-blast equipment at UERL are similar, in principle, to the circuit shown in Fig. 36. Some of the power supplies do not contain a negative output voltage. These are used for supplying the control equipment used in conjunction with the DuMont type 208 oscillograph and in the beam-brightener power supply used in the Mobile Laboratory. Batteries are used for providing bias in the circuit employed for stabilization about ground when the negative voltage is less than 100 v.

These stabilizers have all been quite reliable and have given satisfactory service. The most serious difficulty encountered was in the circuit shown in Fig. 36, in which a change in design required that the plate transformer be operated at rated load. It was found that the transformer became too hot under these conditions even when well ventilated.

(b) Cathode-ray-tube power supply. — The power-supply circuit shown schematically in Fig. 37 is used for supplying power to the cathode-ray tubes in the Mobile Laboratory. One power supply is used to supply the negative potential at from -1150 to -1350 v and another to supply the intensifier potential at positive voltages in the same range. These supplies are designed to operate 24 cathode-ray tubes and the maximum current rating of the supplies is 50 ma. At a load of 15 ma the stabilizer output has approximately 0.125 v, peak-to-peak, of ripple, or about 0.01 percent, and the output voltage changes about 10 v for a change in line voltage from 105 to 125 v, or about 0.05 percent change in output for a 1 percent change in line voltage. Although this degree of stabilization is satisfactory for the present application of the supply, it is believed that the performance can be improved by further study of the stabilizer.

The circuit is similar to that developed by Cole for use in the study of underwater shock waves [33]. A voltage doubler and single-section condenser-input filter are used. Two tubes in parallel (T_3 and T_4) are employed as the series tubes in a degenerative-type stabilizer circuit. These tubes are controlled by a "cascode" amplifier [55] (T_5 and T_6) connected to the output of an unbalanced μ-type circuit (T_7), similar to T_7 in Fig. 36. The main difference between the stabilizer described in Ref. 33 and the stabilizer described here is the use of a balanced μ circuit in the circuit given in Ref. 33.

The two cascode tubes are operated with a plate voltage of 400 v. The plate voltage on T_7 is determined by the VR tube T_8, and the bias on T_6 and the voltage across T_3 and T_4 is a maximum of 600 v. For higher voltage operation additional tubes can be added in cascode, but some difficulty might be encountered in applying higher voltages to T_3 and T_4.

The transformers in this circuit are operated at voltages well in excess of their rated insulation voltages, but no breakdowns have occurred in a year of continuous operation. It is probably advisable, however, to obtain transformers with higher insulation.

By plugging a jumper into the back of the supply either the negative or positive output terminal is grounded and the other terminal is connected to the output plug. A patch cord is used to couple the supply containing the negative jumper with the supply containing the positive jumper so that both positive and negative voltages can be obtained from one plug. The Jones plugs used for high-voltage connections have proven satisfactory, although care must be taken to eliminate excess rosin and stray strands of wire.

The power supply is constructed on a 17X13X3-in. chassis with a standard 8 3/4-in. rack panel. All connections are made to plugs at the rear of the chassis and the circuit grounds are not connected to the chassis.

These supplies have been satisfactory and have not had to be serviced in a year of almost continuous use in which the opportunity for even a routine check was not available.

Chapter 12

COMPLETE BLAST-MEASURING UNITS AND THEIR OPERATION

Two different units have been used at this laboratory for the measurement of air blast. One of these sets of equipment is a mobile unit housed in a semi-trailer and contains eight recording channels. The other set of equipment consists of a number of portable circuits which are designed to be used with the DuMont type 208 cathode-ray oscillograph. This equipment is used in a semi-permanent establishment containing from four to eight channels and in portable equipment containing from two to four channels.

12.1. The Mobile Laboratory

The Mobile Laboratory, which is built into a Trailmobile semi-trailer, contains eight high-gain oscillograph channels for recording air-blast pressure-time curves by means of piezoelectric gauges. The trailer was designed to accommodate up to sixteen piezoelectric channels, but the remaining eight channels have not been constructed. A 1.5-ton truck is used with the Mobile Laboratory to transport all heavy and bulky equipment employed in blast measurements that are not included in the trailer. Together with the truck, the Mobile Laboratory is a completely self-sufficient unit containing all the equipment and materials necessary for blast measurements except for the explosives and such heavy equipment as bull-dozers, graders and cranes. The Mobile Laboratory has been used on field trips of as long as four months duration. The trailer can be transported to any location that can be reached by paved or good dirt roads and, when aided by a caterpillar tractor, can be moved to sites that can only be reached by fairly poor roads.

The Mobile Laboratory was designed to measure the blast from charges weighing from ½ to 10,000 lb. The maximum pressure which can be measured accurately by the electronic equipment is limited by the high-frequency response of the amplifiers; the high-frequency response is a limitation for the measurement of blast from small charges only. The maximum sensitivity of the equipment depends on the length of gauge cable used: with 1000 ft of cable and the most sensitive tourmaline gauges available, the sensitivity is sufficient to measure pressures of about 1 lb/in².

(a) General layout of the Mobile Laboratory. -- The floor plan of the Mobile Laboratory is shown in Fig. 38. The trailer has three doors, two in the sides and one in the rear. The rear door is provided with removable steps and is the door most frequently used. The trailer is lined with balsam-wool insulation covered by plywood.

The inside of the trailer contains a control room, which includes all of the electronic equipment, a darkroom, and a workbench and desk.

(b) Control room and instruments. — The layout of the electronic equipment is shown in Figs. 38 to 41. The general operation of the equipment is described in previous chapters of this report. All power equipment is located together and is removed from the immediate vicinity of the amplifiers, cathode-ray tubes and control equipment. The rotating-drum camera is an integral part of the darkroom.

In addition to electronic equipment, the control room contains the master of an intercommunications system and a small drop-leaf writing table that is used for recording data. The intercommunications system is used for communicating with the field, the darkroom, camera stations, guard stations, and so forth.

Gauge cables are connected to the recording equipment by means of feed-through plugs in a terminal board in the port side of the trailer (CI, Fig. 38). Patch cords run from the cable-inlet panel to the junction box. This panel also contains plugs for the tripper cables used when external trip switches are employed. The tripper plugs are connected to the master control.

Power is connected to the switchboard through a terminal board in the starboard side of the trailer (PI, Fig. 38). This terminal board includes, in addition to connections for AC and DC power to the switchboard, plugs for the circuit used for detonating the charge, plugs for a number of intercommunication lines, and AC and DC plugs for use when power is required outside the trailer. As indicated in Fig. 35, power for the electronic power supplies and current for A6 tube heaters is controlled by one switch on the power-control panel. Patch cords connect the output of the power supplies to a power distribution panel on the wall of the trailer behind the power supply racks (PD, Fig. 38). The DC power for the tube heaters of the amplifiers and for the relays and pilot lights in the control equipment are also connected to this power distribution panel. Batteries for the control equipment, a battery charger, batteries for the firing circuit, and a Varitan for boosting the AC heater voltage, are contained in a box below the master-control power supply (see Fig. 41). Wires from the power distribution panel next to the power supply racks are run in an overhead channel to the power distribution panel behind the instrument racks. The latter panel contains plugs for patch cords to the electronic equipment.

None of the circuit grounds in the electronic equipment are connected directly to the chassis. All of the amplifier circuit grounds are connected to a single wire at the power distribution panel next to the instrument racks and this wire leads to the amplifier power supply. The control equipment and the cathode-ray-tube rack are connected to one wire at this power distribution panel and this wire is attached to the power supply grounds. All of the power supplies are grounded at one point which connects to the negative terminal of the 12-v DC from the generator. The generator chassis is internally connected to this line. The equipment racks are connected together and may be grounded either to the electronic ground or to the trailer chassis. They are fastened to the trailer in such a way as not to be in contact with the metal parts of the trailer frame. The BX on the trailer light and power wiring is connected to the trailer chassis. The ground connection to earth is made in a number of different ways. This is discussed in part (g) of this section.

The arrangement of equipment in the control room is such that one person can easily operate it. Two microswitches, in addition to the trip switch in the step-generator, are included for initiating the step-generator, beam-brightener, and sweep-generator. One of these, which is located to the right of the sweep-generator (see Fig. 39), is used for tripping the equipment while observing the cathode-ray tubes when the camera mirror is open, and the other, which is placed next to the viewing hole by the back of the camera mirror, is used while the tube screens are observed through the viewing hole at the same time a photograph is being taken. When the change is fired from inside the trailer, the firing panel at the top of the left-hand power-supply rack (see Fig. 40 and 41) is used. One person can both fire the charge from this panel and, by means of a cable extension handle on the shutter, simultaneously open the camera shutter.

The back of the equipment, except for the cathode-ray-tube rack, is readily accessible. The cathode-ray-tube rack can be reached through a partition in the darkroom and through a small door in the metal shield on the side nearest the instruments.

(c) Darkroom. — The rotating-drum camera is built into the darkroom so that the camera can be loaded and unloaded simply and efficiently. The darkroom, which is shown in plan view in Fig. 38, contains all the equipment for developing the photographic records, including materials for making up photographic solutions, developing tanks, a sink and a 40-gal water tank. It has storage space for photographic materials as well as additional space for the storage of electronic parts and equipment. The water tank is filled from outside the trailer by a small electric pump and is run into the sink by gravity feed. The sink drain leads to a hose outside the trailer. Film drying racks and a drying fan are provided, and an American Blower Company No. 0 utility set blower is included which can be used to circulate air from the darkroom either into the outside air, or, through a tube leading behind the cathode-ray-tube racks, into the main part of the trailer.

(d) Workbench and desk. — A workbench is provided at the rear of the trailer. The tools, test equipment and parts included are sufficient for the complete servicing of the electronic equipment and for handling most of the mechanical repairs ordinarily encountered.

A desk, which contains all the material necessary for analyzing blast records, is also included. A portable tracer [60] which can be used on top of the desk is provided for measuring records.

(e) Heating, ventilation and lighting. — Heating is provided by a pot-burner kerosene stove at the rear of the trailer. Occasionally an electric hot-plate, used primarily for heating photographic solutions, is also used to provide general heating. Although the walls of the trailer are insulated, the doors and floor are not, and consequently in zero-temperature weather, it takes some time for the trailer to become warm.

Ventilation is obtained by means of an American Blower Company No. 12 Ventura exhaust fan above the drop-leaf desk and by means of the blower in the darkroom. Vents are located behind the instruments racks, in the rear door, and in the darkroom. A fan by the power supply racks is used for ventilating the amplifier power supplies. This amount of ventilation has proven adequate, and air-conditioning has not seemed to be necessary at outdoor temperatures as high as 96°F under conditions of high humidity.

No refrigeration is provided for cooling photographic solutions in summer, and no heating or insulating method is used to prevent the water tank and solutions from freezing when the trailer is not heated for longer than a day.

Except over the workbench, lighting is obtained from bathroom-type porcelain fixtures which are inverted to give essentially indirect lighting. These fixtures are Alabax Porcelain Fixtures AL-2102NI supplied by the General Electric Supply Corporation. This lighting, which employs inexpensive fixtures, has been very satisfactory. Three Ivanhoe shade-holder reflectors are used over the workbench. Type OB33-60 supplied by the General Electric Supply Corporation.

(f) Miscellaneous. — Large storage compartments are provided under each side of the trailer for storing tools used in field work and for other miscellaneous equipment.

A metal box is fastened under the trailer for storing blasting caps.

(g) Operation of the Mobile Laboratory. — Construction of the Mobile Laboratory was started in the summer of 1944 and this unit has been in continuous operation since the fall of that year. Blast measurements have been made on bombs, bare charges and line charges. The smallest charges measured with this equipment have been 2-lb bare charges and the largest charges have been 5000-lb line charges. The Mobile Laboratory has also been employed for studying gauges in the shock tube. This unit has been used at Camp Edwards, Massachusetts and at Camp Hill, Virginia. The results of these measurements are reported elsewhere [1, 53, 61]. The general nature and reproducibility of the results obtained with the Mobile Laboratory are described in Chap. 14.

The Mobile Laboratory has proven to be a very convenient operating unit. The blast-measuring equipment can be set up on a new location in a relatively short time and the operation of the equipment has been found to be efficient.

Certain difficulties have been encountered in the operation of the Mobile Laboratory which have not been entirely solved and experience has shown that certain improvements are in order. Some of these difficulties occur only when long gauge cables are connected to the electronic equipment and some of them occur in the electronic equipment when cables are not connected.

(i) Difficulties encountered in the operation of the electronic equipment. The electronic equipment by itself, without long cables connected, has occasionally exhibited a spurious step-like oscillation. These oscillations occur infrequently and appear on different channels at different times. When they do appear however they last for a few hours or more, and seem to have a fairly regular repetition rate. The step oscillations are more likely to occur when the equipment has been warmed up rather than when it has just been turned on. These oscillations are usually under $\frac{1}{4}$ in. on the cathode-ray tube screen, and although they have rarely interfered with the blast measurements, they have been extremely annoying.

The source of the step oscillations has been partially localized: it is located in the circuits connected to the negative terminal of the high-voltage cathode-ray-tube power supply, and is probably either in the beam-brightener or in the cathode-ray tube rack, neither of which are very well constructed. At times the oscillations can be stopped by barely touching certain patch cords, but this remedy is not reproducible and has not been traced to any definite fault.

There is some evidence that a channel-wise systematic error, amounting to 2 to 3 percent, may exist in the equipment. This effect, if real, causes a difference between the positive impulses recorded on the top and bottom halves of a drum in the rotating-drum camera [53]. Although it was proposed that, since the mirrors in the rotating-drum had to be tilted into a skew position to align the camera, these mirrors might be responsible for the distortion, it has not been conclusively established, that there is a consistent and appreciable distortion, and the evidence has not pointed clearly to difficulties in connection with aligning the mirrors.

As has been pointed out in Chap. 5, certain improvements in the high-gain amplifiers are in order. Occasionally problems are encountered in which the low-frequency response of these amplifiers is not sufficient. Other problems require a greater distance between the gauges and the recording equipment than can be used with the equipment in the Mobile Laboratory. These limitations, however, are in part due to the fundamental characteristics of piezoelectric gauges.

It is probably advisable to improve the wiring in the beam-brightener and in the cathode-ray-tube rack. The writing speed available is adequate for all purposes encountered, but for measurements at high pressures on small charges greater cathode-ray tube intensity may be required. The intensity is sufficient to obtain first-class records of pressure-time curves at a film speed of 2 to 3 msec/in. and greater. Experience has shown that work of a highly experimental nature sometimes requires great flexibility in the choice of film speeds and that the speeds provided in the rotating-drum camera in the Mobile Laboratory do not always permit sufficiently flexible operation. It would also be of value to reduce the size of the blind spot on the film drums and to provide exact synchronization of the blast record and calibration steps with the film drum.

(ii) Difficulties encountered in operation with long gauge cables. These difficulties are threefold. The most serious difficulty encountered in the operation of the Mobile Laboratory has been the sensitivity of the recording equipment to electrical signals which accompany the detonation of an explosive. The equipment is also sensitive to radio signals. Although the recording system is sensitive to 60 cps when long gauge cables are connected, this signal has usually been effectively eliminated. The sensitivity of the equipment to spurious signals is a fundamental characteristic of high-gain, high-impedance systems. The signal picked up from the explosion is usually manifested as hash and occurs before or during the time that the blast wave strikes the gauge. The hash is sometimes accompanied by a step displacement of the baseline, and the hash may continue for as long as 10 to 20 msec, although sometimes it is of very short duration. The signal is generally more pronounced when the gauges are close to the explosion, but signals have been picked up by gauges recording pressures as low as 12 lb/in.^{2} The signal is not reproducible: tests were made in which no part of the equipment or field layout was changed from one shot to the next; on some shots a large signal was obtained but on others none was evident. No signal seems to be produced by a blasting cap. Another signal, which is usually too small to be troublesome, is sometimes picked up from the current used to initiate the charge. The troublesome hash, however, never occurs before the detonation takes place. (The explosion occurs a short time after the current is applied to the detonator.)

Experiments have indicated that some of the hash may be transmitted over the firing line. The firing circuit has been placed outside the trailer in an attempt to reduce the signal; this procedure probably had a slight effect in reducing the signal. There is no direct connection between the firing circuit and any of the electronic circuits. The tripping circuit is connected to one circuit of the firing relay, but the firing circuit is on a separate contact of the relay. The firing line is always placed at fifty feet or more from the gauge cables except where it connects to the trailer and to the blasting cap.

The major part of the signal is probably transmitted by the gauge cables but it is not known whether it is transmitted over the cable shield or over the central conductor. There is a small amount of evidence, however, to indicate that it is transmitted over the shield. The signal does not appear to be reduced when two cables are laid out to form a balanced system.

It is believed that the grounding of the equipment has an important effect on this signal. However, the grounding of a long-lines blast-measuring system is not a simple matter. In addition to direct connections to ground, the cables, the trailer, and the generator all have a large capacity to ground, and furthermore it is difficult to maintain a high leakage resistance between all these elements and the earth. Experiments have been conducted in which the entire system was disconnected from the earth and in which the leakage resistance was 50,000 ohms or greater. Other tests have been made when the Mobile Laboratory or the gauges were connected to the earth either separately or together. Although no very conclusive results were obtained from these experiments, it is considered better to make the ground connection at the gauges and to leave the electronic equipment floating.

Two hypotheses have been proposed to account for these signals, but they have not been corroborated. One is that the electrical signals produced by the explosion induce a signal between the gauges and the earth. The other is that the ionized gases surrounding the explosion tend to short the gauges to earth, thus producing a signal if any potential exists between the gauges and the earth. In a series of tests in which the Stanolind Oil and Gas Compnay collaborated with this laboratory, the Stanolind equipment picked up a signal of this type probably on a line extending to the field tripper. When the tripper was connected to earth and the electronic equipment, which was originally earthed, was left floating, this signal was eliminated.

The type of gauge cable employed may effect the signals picked up from the explosion. Both the character of the shield and the nature of the insulation between the shield and the earth may have an affect, and a twin-ax cable may behave differently from the two co-axial cables used to form a balanced system. Unfortunately all the tests made with the Mobile Laboratory have been with Telconax cable. The only other remotely comparable experiments conducted at this laboratory were made with lead-sheathed cable which was buried in the ground for a distance of 100 ft behind the gauges. Since the Mobile Laboratory was not used in these experiments, no direct comparisons can be made. It may be possible that the cable must be well grounded for some distance behind the gauge, as for instance in the test made with the lead-sheathed cable. A heavy shield may also be necessary.

Radio signals from low-frequency radio stations have been picked up at a number of locations. The Mobile Laboratory has recorded signals of about 18 kc/sec at Camp Hill, Virginia. At Camp Edwards, Massachusetts, signals were picked up from a powerful long-wave station and from a Loran transmitter. Other blast-measuring groups have also been troubled by radio signal.

When the gauge end of the cables are grounded or have a low leakage to ground, the equipment seems to be more sensitive to radio signal than when the gauge end of the cables is left floating. A low impedance between the central conductor and shield of the cable when there is a leakage between the shield and earth seems to emphasize the signal. Balanced cables reduce the signal somewhat, and the longer the cable the greater the signal. It is believed that a cable with a heavier shield than those ordinarily used should reduce this type of pickup, and that perhaps a cable with two shields, insulated from each other, might be effective.

As a rule 60 cps pickup is reduced most readily by connecting the electronic equipment to the earth. When this equipment cannot be grounded because of pickup of radio signal or signal from the explosion, 60 cps pickup may become troublesome. Under these conditions it has been found that balanced cables are very effective in eliminating this pickup. It is important, when the electronic equipment is not grounded, that the generator, and power lines to the generator, be well insulated from the ground.

12.2. <u>Blast-measuring equipment using the DuMont type 208 oscillograph</u>

The equipment used with the modified DuMont type 208 cathode-ray oscillograph has been employed in a semi-permanent installation containing two sets of four channels and as portable equipment comprised of two to four channels. This equipment is fundamentally limited in application by the characteristics of the oscillograph, but it has been employed in the measurement of blast from bare charges weighing from less than a pound up to 40 lb and on bombs up to 2000 lb. Equipment of an essentially similar nature except for the use of field preamplifiers has been employed, for the measurement of blast from 4000- and 10,000-lb bombs [18, 25].

(a) <u>Equipment used with the DuMont oscillograph</u>. -- The blast-measuring equipment using the DuMont type 208 oscillograph contains the following additional equipment:

(1) Preamplifiers, and preamplifier power supplies,

(2) Sweep-generators or beam-brighteners,

(3) Fixed- or moving-film cameras,

(4) Control and calibrating equipment.

Most of this equipment has been described in previous pages of this report or is similar to the equipment used in the Mobile Laboratory.

(b) <u>Permanent installation of equipment</u>. -- The permanent installation of equipment is located on Nonamesset Island, which is about 3/4 mi from Woods Hole. The eight channels included in this installation can be operated as a single eight-channel unit or, with gauges on two different sites, as two four-channel units. This installation is not generally used to investigat charges larger than 4 lb, but the blast from charges as small as 0.05 lb has been measured.

The arrangement of equipment in a four-channel unit includes one relay rack and two roller tables. Two oscillographs are placed side by side on each roller table and a sweep-generator is placed in a small relay rack under the oscillographs. The large relay rack is used for the control equipment and the preamplifiers, and is located to one side of the roller tables. Rotating-drum cameras are mounted in the wall of a darkroom and the oscillograph tables can be rolled up and the oscillographs fastened to the removable light-tight hoods of these cameras. When cut-film cameras are used the roller tables are moved back and the hoods from the rotating-drum cameras removed. No connections have to be changed to transfer from cut-film to drum-film operation. The two four-channel units are similar, and are arranged side by side so that the control racks are adjacent to each other. Enough space is left between the control racks and at the ends of the oscillograph tables for a passageway, and the back of the equipment is completely accessible.

Power is controlled in much the same way as in the Mobile Laboratory except that one switchboard is used for each set of four channels. The two switchboards can be interlocked, however, so that all the power can be controlled from one board if desired. Two Onan 5-kw generators are available; one can be used for each set of four channels. The electronic power supplies for the preamplifiers and control equipment are located at some distance from the recording instruments. The oscillographs and sweep-generators have self-contained power supplies.

Connections to the field are made through a panel in the wall of the building which houses the equipment.

(c) Portable use of equipment. — On occasion, particularly before the Mobile Laboratory was constructed, the DuMont oscillographs and auxiliary equipment have been employed as portable units. Four channels have been transported in a 3/4-ton truck for installation in a bombproof at the recording site or have been semi-permanently installed in a moving van. Two-channel units have also been used. The control equipment constructed for use with two channels has not been as completely coordinated as that used for four-channel operation.

(d) Operation of equipment using the DuMont oscillograph. — Blast-measuring equipment was constructed at Harvard University in 1942 by personnel now on the UERL staff. This equipment, briefly described in Refs. 16 and 25, employed field preamplifiers and DuMont oscillographs, and was used in 1942 and 1943 at the Aberdeen Proving Ground in tests on 4000- and 10,000-lb bombs, made in cooperation with the Ballistic Research Laboratory. The equipment was developed to its present form in 1943 and 1944, the main changes since the spring of 1944, aside from minor improvements, being the inclusion of control equipment.

Before the construction of the Mobile Laboratory the equipment using the DuMont oscillograph was employed for the measurement of blast from larger charges than could be measured in Woods Hole. In addition to the early tests made at the Aberdeen Proving Ground, this equipment has been used for measuring blast pressures from large charges at the Jefferson Proving Ground, Madison, Indiana; Camp Edwards, and Wellfleet, Massachusetts; and at the Factory Mutual Corporation, Norwood, Massachusetts. This equipment has also been employed for studying gauges in the shock tube. The major part of the air-blast measurements which have been reported by UERL were made with this equipment. Those results are summarized in Refs. 1, 5, 60, 61 and 62.

Although the results obtained with this equipment have been, for the most part, of the same caliber as those obtained with the Mobile Laboratory (see Chap. 14), the equipment using the DuMont oscillograph has not been as convenient or as efficient to operate. Essentially, this equipment is a makeshift adaptation limited by the characteristics of the oscillograph. The low-frequency response of this equipment is not as good and the gain not as high as the equipment in the Mobile Laboratory.

The most troublesome feature of this equipment is the presence of 60 cps hum. Part of the hum comes from the preamplifier power supplies and limits the maximum usable sensitivity of the equipment under any conditions, but in some arrangements of the equipment ground loops and magnetic pickup have caused additional 60 cps hum. It is difficult to prevent ground loops in this equipment because of the many ground connections between chassis, power supplies and amplifiers, which are essentially determined by the construction of the oscillograph. The transformers in the oscillograph and sweep-generators have been sources of magnetic pickup which are often very troublesome. This equipment operates reasonably well in a permanent location after the ground loops and sources of magnetic pickup have been eliminated, but when setting up in a new location considerable difficulty has sometimes been encountered before the pickup could be sufficiently reduced.

The records obtained with the units involving the DuMont oscillograph are not, in general, as good as those obtained in the Mobile Laboratory. A number of factors contribute to these differences between the two units. The most important is the existence of noticeable 60 cps hum and a certain amount of instability in the equipment used with the DuMont oscillograph as compared to the absence of these particular spurious signals in the Mobile Laboratory. In the former the available cathode-ray-tube intensity is, on the average, not as great and the focus not as good, as in the Mobile Laboratory. In the equipment using the DuMont oscillograph the records obtained with fixed-film cameras are not as good as those obtained with rotating-drum cameras.

In only one series of tests was the equipment employing the DuMont oscillograph used with gauge cables comparable in length to those employed with the Mobile Laboratory. Neither pickup from the electrical signals accompanying the detonation nor radio signal were troublesome in these tests, but it is not known whether this results from a characteristic difference between the two units or whether it may arise because of differences between the conditions of this experiment and those in which the Mobile Laboratory was employed. In the first place, it is not known if radio signal was present at the site where these tests were made, and in the second place, the cables used were lead-sheathed cables buried in the ground for 100 ft behind the gauges.

Chapter 13

OPERATIONS IN THE FIELD*

It is the purpose of this chapter to call attention to a few factors which are usually encountered in making air-blast measurements and to which the experience of this laboratory is pertinent. It is a considerable step from a set of apparatus which works well in the laboratory to its operation, under field conditions, in measuring air blast.

13.1. The test site

(a) The location. -- A site which is suitable for detonation of explosive charges and bombs must be one which offers no hazards to persons or property in neighboring communities. The distances between the site and the nearest inhabited buildings, public highways, and so forth, depend upon (1) the maximum size of charge to be detonated; (2) whether or not it has a metal case; (3) the nature of the terrain over which the blast will pass between charge and dwelling, and (4) to some extent, the nature of the charge, particularly its shape. It is not sufficient to consider the range at which fragments from bomb casings, and so forth, are dangerous to persons and property. It is usually assumed that a safe distance (considering fragments only) from the detonation of a 500-lb GP bomb, for example, is about 1000 yd. On the other hand, major blast damage would be limited to distances much less than 1000 yd, but minor damage to light residential structures might occur at greater distances. Damage to plaster occurs when walls are accelerated 0.1 to 0.3 g [49]. For a light frame house, this acceleration might be observed as far as two miles from the detonation of a 500-lb GP bomb. In some cases in practice, no difficulty has been encountered when bombs as large as 2000-lb GP were detonated at a distance of about 2 mi from inhabited dwellings. From observations made at Aberdeen Proving Ground [50] it was concluded that the limit of superficial damage (broken glass and cracked plaster) was at a distance $R = 3750 \sqrt[3]{w}$ where R is measured in feet from the site of the explosion and w is the effective charge weight in pounds. For a 500-lb GP bomb, this gives about 4 mi as the limiting distance -- a figure about double that of the above estimate.

Under conditions very favorable for the propagation of the blast, glass has been broken at a distance of 1 mi from a charge weighing 15 lb. The formula above predicts about 2 mi as the limiting distance for this charge weight. In this case, the blast travelled for about two-thirds the distance over water -- a condition known from experience to be most favorable for blast damage. Occasionally, special features of the terrain such as hills and valleys, the latter leading toward habitations, will produce marked asymmetries in the safety limits around the detonation site. Intervening forests and hills, on the other hand, tend to reduce the limits of minor damage.

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*This chapter was written by R. F. Arentzen

When a large "line" charge was detonated in recent tests, there were some indications that the minor damage observed in directions perpendicular to the charge was greater than that in the direction of the charge axis. This effect should not be appreciable at very great distances from the charge.

The location of a site for detonation of high explosive bombs and charges must also be chosen with other factors in mind. Aircraft flying over the site must be protected by a careful warning system. If the site is close to an airport this necessary vigilance and the consequent interruptio of operations are annoying. Nearby power or telephone lines may be cut by flying fragments, and for this reason, a site should not be located near such lines. It is highly desirable to locate the site in such a position that trespassing on the danger area is prevented, and, if possible, so that the only access to the detonation site is by a path or road leading past the recording shelter.

(b) The distance from charge to recording station. -- The distance from the charge to the bombproof and recording station should be sufficiently great that no blast damage to the structure or the equipment will occur, and so that, for a given structure, no fragments can penetrate the bombproof protection. On the other hand, for reasons of expediency, the charge-to-bombproof distance should be no greater than that necessary to insure safety.

For bombs and cased charges as large as 10,000 lb, a distance of 900 to 1100 ft from charge to bombproof has been adequate. For small bare charges, a shelter of light frame construction was undamaged at a distance of 50 ft from a 4-lb charge. Ordinarily, with this shelter, for charges up to 4 lb in size, a distance of 200 ft from the recording station was used.

The distances quoted above are not necessarily the smallest which could have been used. In only one case, in the experience of this laboratory, was the bombproof located too close to the charge. This occurred during blast measurements on line charges at Camp A. P. Hill, Virginia, when an M-3 Snake, containing 4700 lb of Amatol 80/20 in the form of a 320-ft line charge was detonated. The bombproof was located about 750 ft from the side of the Snake, and the end of the bombproof away from the charge was open.

The Mobile Laboratory (see Chap. 12) had been backed into the bombproof. During the shot, all doors were latched. The rear steel doors, which were bolted shut by means of a steel rod of 5/8-in. diameter in sockets in the floor and roof, were blown open, presumably because of the suction of the blast. The steel rods were bent badly in the process. The vehicle was severely jarred, and the roof and walls were displaced without apparent permanent damage. A rough estimate of the blast pressure is 1.5 lb/in.^{2} and of the positive impulse 30 lb-msec/in.^{2} at a distance of 750 ft from the charge [53]. It is difficult to estimate the magnitude of the negative pressure in the suction, or the pressures actually exerted on the vehicle inside the bombproof.

(c) The size of the test site. -- The area required for static detonations of high-explosive bombs and charges is determined by the size of charge, whether the charge is a "point" or "line" charge, the distances to which pressure measurements are to be made, and whether the measurements are to be made in "free air" or on the ground.

For the detonation of bombs up to 2000-lb GP, an area about 200 ft X 300 ft is required. This area should be level and cleared of grass, shrubs, and trees. Pressures down to about 3 lb/in² can be measured with 2000 lb GP bombs, on such a site.

For small charge air-blast measurements, the test area can be smaller. For example, an area 50 X 100 ft suffices for blast measurements on charges up to 50 lb in weight.

Although the area must be level and free of undergrowth for blast measurements made with gauge and charge on or near the ground, this is not necessary where "free-air" measurements are to be made. However, setting up gauge and charge mounts, and so forth, is greatly facilitated when the ground is level.

In all cases, it is advisable to compute the times required for reflections of shocks from banks, ravines, trees, and so forth, to arrive at the gauges, and to compare these times with the time required for recording that part of the pressure-time curve of principal interest.

Because of the size of the charge itself, a line charge requires a larger test area than does a point charge of the same weight.

(d) Miscellaneous considerations on selecting a test site. -- (1) Relative elevations of the detonation site and recording station are not critical. However, if the bombs can be detonated in a valley, the area of principal fragment danger is thereby limited. Advantage can be taken of the contours of the ground to protect the coaxial gauge cables from missiles. If the elevation of the bombproof is somewhat greater than that of the charge being detonated, moving-picture photography of the detonation is facilitated.

(2) The nature of the soil has an important bearing on the ease with which experimental blast measurements can be carried out. Rapid drainage assures that there will be a minimum of interference with the work in rainy weather. The soil should preferably not be rocky, since the erection of charge and gauge supports, digging trenches for protection of cables, and so forth, are more difficult in rocky soil. Sand or very loose earth make it necessary to use "dead-men" as anchor-points for guy wires, and so forth, since stakes will not hold at all in such soil. A dead-man is a broad plank or log buried two or three feet in the soil, with wires wrapped around it and leading to the surface of the ground.

The nature of the soil influences the size of the crater resulting from the detonation of the charge. Since most experiments involve detonating a series of charges on the same spot, it is necessary to fill the crater after each round. It is important that the absorption of energy by the ground be as reproducible as possible, and hence that the craters be filled and compacted reproducibly. It is necessary that soil for filling craters be readily available near the detonation site.

(3) The climate of the region determines the ease or difficulty of blast measurements. Since high leakage resistances in cables, gauges, and other equipment, are essential, a dry climate is the most favorable. There is evidence [51] that a charge fired in light rain or fog will produce from 10 to 15 percent less blast impulse than one fired on a clear day.

Extremes of temperature may affect gauges, cables, and other apparatus. For example, a great deal of difficulty has been experienced by this laboratory with Telconax cable in very hot weather, when the dielectric softened and short circuits resulted, and in very cold weather, when the outer jacket of the cable cracked.

A region of prevailing high winds presents other difficulties. Variable winds produce variable results. Blast pressures and impulses are affected by the direction and velocity of the wind. If measurements of shock velocities are to be made, the wind can have particularly serious effects.

13.2. The bombproof

The purpose of the bombproof is to protect personnel and apparatus from fragments and from blast. It may be constructed of almost any material providing that the material is sufficiently strong and thick to resist penetration by even the fastest fragments. Wood is not very effective. The following thicknesses of various materials probably provide sufficient protection for a bombproof at 1000 ft from a 2000-lb GP bomb: mild steel, 1 in.; concrete, 8 in.; hard wood, 35 in.; soil, 50 in. [52].

Several types of bombproof have been used by this laboratory. Of these, the best was a steel Quonset hut covered with earth about 2 ft thick on top, and as much as 10 ft thick on the end facing the charge. It was necessary to dig a trench about 4 ft in the earth under the shelter to give clearance for the Mobile Laboratory, which is 11½ ft high. A drainage ditch across the open end kept the interior of the shelter dry. The end of the hut facing away from the charge was left open for convenience. Another type of bombproof consisted of an end wall about two foot thick, and a roof about one foot thick, constructed of logs. The end wall, which faced the charge, was protected by a layer of sandbags about 3 ft thick and by steel plates ½ in. thick. Some blast protection is afforded by such an arrangement, since the blast cannot strike the Mobile Laboratory head-on. A similar bombproof, with wooden wall and roof, protected on the end facing the charge by 3 in. thick armor plate has been used. This was certainly more protection than was needed.

13.3. Explosive charges

(a) Precautions in handling explosives [54]. — Explosive materials must be handled with great care. They must be protected from shock, heat, friction, electricity and sparks. All initiating devices are extremely sensitive, and they should be kept away from the charge until the last possible moment. Detonator caps should never be carried in pockets and their lead-wires should be shorted together until the detonator is attached to the firing line.

The number of persons exposed to danger from explosives should be held to a minimum at all times. On the other hand, at least two persons should be present whenever explosive charges are being handled, and one of these persons should remain at a safe distance from the charge.

The regulations issued under the Federal Explosives Act [54] stipulate that a license must be obtained by foremen handling explosives.

(b) Transportation of explosives. — In order legally to transport explosives, the vehicle must be licensed by the state. The type of vehicle, construction of body, and so forth, are specified by law, and the vehicle must be inspected and approved prior to granting a license. These requirements vary from state to state, and the vehicle must be licensed in each state in which it is to travel, when it is transporting explosives.

Small bare or cardboard-cased charges should be packed in excelsior in wooden boxes, and the boxes so stowed that they will not slide and bump each other.

Cased charges and bombs can be carried in a truck, using heavy timber as dunnage between the bombs. The bombs should be held from moving by this dunnage and by ropes. Great care in handling bombs is required. Accidental explosions have occurred when unfuzed bombs were dropped as little as 3 ft.

Initiators such as fuzes, detonator caps, and so forth, should never be transported in the same vehicle with high explosive charges.

(c) Storage of explosives at the site. — It is necessary to provide temporary storage facilities near the site for the charges to be used on a given day. This may consist of an area set aside for the purpose, sufficiently removed from the detonation site that the stored charges are safe from shock, fragments and flame, and sufficiently removed from the recording site that personnel would not be exposed to risk in case of accidental explosion. With bombs, the principal danger is from fragments of the case; the radius of danger from fragments is about 1000 yd from a 500-lb GP bomb. With bare charges, there is little danger from missiles, and blast is not a very great hazard. The blast pressures which offer various degrees of risk are listed below.

Degree of Injury	Peak Pressure in Blast (lb/in²)
50 percent chance of fatality	400
50 percent chance of broken eardrum	7 to 15
None: safe on repeated exposure	3 to 5

For example, at about 100 ft from a 500 lb GP bomb, the pressure is about 4 lb/in^2, and repeated exposure to this pressure would not be harmful; however, the risk from fragments at this distance would be very great.

During a recent series of trials of 500-lb GP bombs, it was convenient to carry all bombs for the day in a truck, with adequate dunnage and fastenings. The bombs were arranged in the truck in the order in which they were to be fired. After a bomb was unloaded and set up for detonation, the truck with the remaining bombs was driven well outside the danger area and well away from the recording station.

(d) Fire prevention. -- Inflammable material near the detonation site of an explosive is very likely to be set on fire by the flame from the explosion. Fires farther from the explosion may be started by the fragments from cased charges, particularly those of aluminum or magnesium, and by the burning particles from an incomplete detonation. Fire prevention apparatus should always be on hand and, wherever possible, a large area surrounding the test site should be cleared of anything inflammable.

(e) The charge support. -- The requirements of supports for charges for static detonation are as follows:

a. The charge must be readily fixed in space.

b. The orientation of the charge with respect to gauges, and so forth, must be readily fixed.

c. The support must have no appreciable effect on the blast by reflection, and so forth.

d. The support must be safe.

e. The support should be portable, whenever possible.

f. For some experiments, the charge must be supported at readily variable heights above the ground.

For small charges which are to be supported well above the ground (so that "free-air" pressure and impulses are measured), it is convenient to support the charge by light strings from a wire or set of wires which will not be damaged by the blast. For supporting the charge horizontally, a light stick can be taped to the side of the charge. String can be used as guys to prevent the charge from swaying or twisting. Such an arrangement is illustrated in Fig. 42. An alternative support which is useful for somewhat larger charges is shown in Fig. 43. With both of these supports, the charge-to-ground distance can be readily varied.

Supports for bombs present greater difficulties, since the bomb fragments will damage the support, probably beyond repair. Thus it is necessary to provide a new support for each bomb. For supporting bombs as large as 2000 lb some distance above the ground, supports were constructed of tree trunks, heavy planks and wire. Figure 44 shows this type of support. Various heights of bomb up to about 70 ft could be obtained by this method. Bombs as large as 10,000 lb have been supported at smaller heights by a similar method. A crane was necessary for raising the pole, and guy wires were used.

Measurement of the height of the bomb was made by a surveyor's steel tape, the tape being tied to the central lug of the bomb prior to hoisting. For arming the bomb, a wooden platform was lifted by a crane and the person who was to do the arming was carried on the platform. This person also released the steel tape from the bomb.

If all bombs are to be supported at the same (small) height above the ground, a support such as shown in Fig. 45 is useful. By supporting the bomb with its nose about 18 in. above the ground, the crater was kept relatively small, and there was ample space for fuzing and arming the bomb.

(f) Arming the charge. — By arming the charge is meant the insertion into it of the initiating device which is attached to the firing line and the preparation of the initiating device for detonation. It is at this time that the greatest hazard is encountered. The following safety rules are considered necessary in order to minimize the risk:

1. The firing line must at all times be shorted at a safe distance from the charge until the time of use.

2. The point at which the firing line is shorted should be plainly visible to the person attaching the detonator.

3. The firing line must be clearly marked so that there is no chance of confusing it with any other line in the field or at the bombproof.

4. For attaching the firing line to the firing circuit, plugs should be used which are unique and of a type not used elsewhere in the apparatus. This connection should be made via a "jumper" consisting of two male plugs connected by a short length of two-conductor wire. The end of the firing line and the output end of the firing circuit then are terminated with female plugs, and no electrical connection between the two should be possible without the use of the jumper.

5. The jumper should be carried by the person while he is arming the charge.

6. The firing circuit should be completely isolated from all other electrical circuits.

7. The firing line should be tested for continuity and absence of short circuits before preparing to arm the charge. This precaution prevents many misfires. The ohmmeter used for testing the continuity of the line should be applied at the field end of the cable, rather than at the control end, in order to avoid the possibility of a detonator being on the line while it is tested.

8. The detonator cap or initiator should be attached to the firing line before it is inserted into the charge. Lead wires of sufficient length to allow the person attaching the detonator to the firing line to be out of danger should be used.

9. Good means of communication and intelligent use of it help to prevent accidents. The person arming the charge should inform other persons to that effect, and should make sure that the firing line is shorted and is properly disconnected from the firing circuit.

When small charges are supported many feet above the ground, it is often inexpedient to insert the detonator after raising the charge. Instead, the detonator is first connected to the firing line, and then inserted in the charge while the charge is supported at a convenient height. The winch by means of which the charge is raised should in this case be sufficiently removed from the point below the charge that, should the charge fall and detonate, the winch operator would not be in danger.

13.4. <u>Handling of gauges</u>.

(a) <u>Gauge supports</u>. — Gauges may be mounted flush with the surface of the ground, or of a target structure, or of a baffle; or they may be mounted at various distances above the ground. For the last-named type of use, gauge mounts which provide flexibility of application are particularly desirable. The features which a gauge mount should possess to be most useful are as follows:

1. The gauge must be fixed in space.

2. The height of the gauge above the ground should be easily altered.

3. The mount should be readily moved from place to place.

4. The mount should afford some protection for the gauge cable from blast and fragments.

5. The support should offer little reflecting surface to the blast wave, so that the recorded gauge signal will be negligibly affected by the support.

For experiments in which the gauge was located several feet above the ground, the type of mount shown in Fig. 46a proved particularly useful. A variant of this mount involves welding a pipe coupling to the support pipe a foot or two above the lower 90° bend, and screwing into this a piece of pipe which extends below the bend into the ground. A stake formed of somewhat larger diameter pipe can be used as a socket for this projecting pipe. This arrangement was developed by the Stanolind Oil and Gas Company [20]. The advantages offered by the use of a concrete base are that it is readily moved, and can be used on very soft, rocky or frozen ground where stakes are useless. When these supports are used to mount gauges 12 ft or more above the ground it is necessary that guy wires be attached to prevent the supports from swaying.

When gauges are to be mounted very close to the ground, a mount such as that illustrated in Fig. 46b has been used.

(b) Protection of gauges. — When bombs or other charges having a metal case are used, the fragments of metal emitted by the explosion may strike the gauge. If this occurs the gauge is usually damaged beyond repair, and even the record, which would otherwise have been obtained with that gauge, is lost since the fragments precede the shock wave.

When the gauge is supported above the ground, the only means of protecting it from fragment strikes is to interpose an obstacle capable of stopping the fragments. This obstacle, of course, must not produce any appreciable difference in the shock wave recorded by the gauge. In some static detonations of 500-lb GP bombs, a steel pillar 4 ft tall and 6 in. in diameter was erected about 10 ft in front of the foremost gauge in a line of gauges. All gauges were carefully lined up behind the pillar so that fullest advantage was taken of its protection. This precaution prevented many losses, but was not completely successful, since the fragments appear to curve.

Another method of protecting gauges from fragments consisted of erecting a much smaller obstacle — say a 1-in. diameter pipe — between gauge and charge, a distance of about 1 ft in front of each gauge.

Experiments have shown that an obstacle located at a distance equal to or greater than ten times its own diameter in front of a gauge will not appreciably affect the shock wave which reaches the gauge.

(c) Maintenance. — The principal servicing which a gauge must receive while it is in use in the field is the maintenance of high leakage resistance between the central conductor and shield. Just how high this leakage resistance must be is determined by the duration of the phenomenon being observed [see Sec. 1.1(d)]. With 1000-ft cables having a capacity of 40,000 $\mu\mu$f, and a compensating condenser of equal capacity, a leakage resistance of 50 megohms provides an input time-constant of 4 sec, which for bombs as large as 10,000 lb is quite adequate.

The sources of leakage in the gauge are usually either a broken coating on the gauge or moisture in the plug attached to the gauge. If the coating on the gauge is broken, and moisture seeps in, the resulting leakage may be remedied sometimes by baking the gauge in an oven. The occurrence of cracks can be prevented by frequent inspection, and by smearing suspected surfaces with silicone grease, as a temporary measure, or by patching the gauge coating [8] with Bostik cement, Zophar wax, Tygon, or similar compositions. (Bostik cement is manufactured by R. B. Chemical Company, Zophar wax by Zophar Mills, and Tygon by U.S. Stoneware Company.)

If leakage develops at the electrical connector, it is usually easily remedied by heating the plug, after disconnecting it from the gauge cables, with a blowtorch. In order to prevent this leakage, the plugs of gauge and cable after being coupled, are taped, first with rubber tape and then with friction tape.

It is good practice to maintain the leakage resistance as high as possible, since progressive deterioration of the plugs, and so forth, is thereby prevented. It is relatively easy to maintain a leakage resistance of 500 to 1000 megohms.

13.5. The field use of cables

(a) Handling. -- Handling cables may require considerable care. Telconax [see Sec. 4.1(b)] is mechanically quite weak, and requires care to prevent formation of short circuits or actual breaks in the cable. In hot weather it tends to soften and is easily shorted or broken. In cold weather it will crack readily, and moisture can thereby cause trouble. It is safest to dispense the cable from reels, with men stationed at 200-ft intervals to take the strain.

(b) Location. -- The location of the coaxial recording cables in the field should be separate from that of all other cables, principally in order to prevent picking up unwanted signals from them. Near the charge, these cables should be led up to the gauge along a radius from the charge, in order to minimize the length exposed to blast, and to take advantage of the protective posts erected in front of the gauges.

(c) Protection. -- The cables should be protected from fragments and from very high blast pressures. Besides the protection afforded by steel pillars, and so forth, cables may be buried in ditches, and even threaded through pipe. This is a laborious procedure, and is usually done only quite close to the bomb.

Even the best cables tested for sensitivity to shock produce a signal at high shock pressures [see Sec. 4.1(a)]. This can be prevented by threading the cables through pipes and by burying them. There are many disadvantages to the use of pipe; the weight of pipe is considerable, the labor of installation is great, the pipes tend to fill with silt in rainy weather and to freeze to the cables in cold weather.

(d) Leakage resistance. -- High leakage resistance in the cables is just as important as it is in the gauges. The sources of trouble are the plug connectors and cracks in the jacket of the cable. Prevention of leakage of water into the plugs can be accomplished by taping the joint well with rubber and friction tapes. The cables should be inspected occasionally for cracks and abrasions, and these spots coated with a waterproofing material such as Bostik cement.

13.6. Communications

In field work with high explosives it is usually convenient to have one person in the recording station and others at the detonation site. During the day's work, there are very frequent occasions for communication between the two. Notebook entries of distances, weather observations, gauge numbers, charge identifications, and so forth, can be made most conveniently in the recording station; and requests for tools, tests of cable resistance and continuity, "tap" testing of gauges, and so forth, require an easy means of communication. (To perform a "tap" test, one person taps the gauge lightly with his fingers and another observes the deflection produced on the oscillograph. It is used to indicate continuity and polarity in the gauge circuit and to check the channel to which a given gauge is connected.)

The most satisfactory means of communication in the experience of this laboratory is a simple office-type intercommunication system with the "master" in the recording station and a "remote" on the field, attached to a generous length of line which can be pulled about from one place to another.

13.7. Miscellaneous techniques used in field operations

The clearing of large level fields is usually done with bull-dozers and earth removal equipment. When gauges and charges are on the ground, since a very smooth field is required, a grader is more suitable for filling craters and for the final smoothing than is a bull-dozer. The field is usually dragged after being smoothed with a grader.

Ordinary gardening and ditch-digging tools should be on hand in sufficient quantity. The tools most frequently used are: shovels, pick axes, sledge hammers, rakes, mattocks, hand axes, crow bars, hammers, saws, levels, and squares.

The tapes used for measuring distances should be of steel and of the open framework (open cased) variety. Closed cases tend to fill up with dirt, rendering the tape very difficult to reel and unreel. Tapes should be graduated in tenths and hundredths of a foot, rather than in inches and fractions of an inch, to simplify the analysis of data. Hundred-foot tapes have been found the most convenient.

Chapter 14

RESULTS OBTAINED WITH THE BLAST MEASURING EQUIPMENT

Typical oscillograms obtained with the equipment described in this report are shown in Fig. 47. Records (a) and (b), which were obtained in the Mobile Laboratory, each contain two pressure-time curves recorded by gauges placed at two different distances from the same explosion. These records also contain three charge-calibration steps and a simultaneous timing calibration. Record (c), which was made on a cut-film camera, was obtained from the equipment of which the DuMont type 208 oscillograph is a part. This record contains two pressure-time curves which were recorded by the same gauge from two different explosions; the oscillogram also contains two calibration steps and one timing calibration for each of the pressure curves. On these films except on the lower pressure-time curve on record (c), time increases from left to right. On the lower part of the cut-film record time increases from left to right when the figure is turned upside down. The techniques used to measure these oscillograms are reported in Ref. 60.

The pressure-time curves in record (a) were obtained from a 10-lb bare charge. The lower pressure-time curve on this record, which can be seen at P in the figure, is the oscillogram obtained with a tourmaline gauge of the metal center-tab construction. The peak pressure and positive impulse recorded on these oscillograms are given in the table. The timing wave is in the center of the record.

Peak Pressures and Positive Impulses Recorded on Oscillograms

Record	Peak Pressure[a] (lb/in²)	Positive Impulse[a] (lb-msec/in²)	Frequency of timing calibration (cps)
(a) Upper Oscillogram	58.3	40.9	500
Lower Oscillogram	18.4	17.5	
(b) Upper Oscillogram	30	79	500
Lower Oscillogram	16.2	49	
(c) Upper Oscillogram	7.56	17.9	1000
Lower Oscillogram	9.24	18.6	

[a] These measurements are not corrected for the air-flow effect. The methods of correction will be found in Ref. 8.

The upper pressure-time curve on this oscillogram, which is at a higher pressure than the lower curve, is somewhat more irregular in shape than the curve at the lower pressure. This increased irregularity at high pressures is a general characteristic observed in blast records. Slight fuzz, which is from an electrical signal picked up from the explosion, can be seen on the film preceding the peak of the pressure-time curve. The second peak on the upper curve is the signal recorded by a gauge which, together with the primary pressure gauge, is used to measure the velocity of propagation of the shock front. The peak pressure in the blast wave may be calculated from the velocity of propagation.

The three charge calibration steps can be seen at S_1, S_2 and S_3 on this record. The duration of the trace on steps S_1 and S_2 is short while that on S_3, the step used to determine the time constant of the equipment, extends almost completely around the film. The three steps and the blast record are displaced vertically from each other.

The effect of the lucite strip used to hold the film to the film drum can be seen at the two ends of the film, where defocusing occurs.

Record (b) contains pressure-time curves obtained from a 500-lb GP bomb. Both of the gauges used in recording this oscillogram were of the old-type construction without a metal center-tab. The small oscillations which can be seen on these oscillograms just in front of the peak of the pressure-time curve are caused by the bow waves from the fragments which precede the shock wave. This "fragment hash" continues for a few milliseconds after the gauge has been struck by the blast wave. Many pressure-time curves from GP bombs show considerably more fragment hash than is exhibited on these records.

The two pressure-time curves in record (c) were obtained from 40-lb bare charges. The gauges used were of the old-type construction without a metal center-tab. On the oscillogram of the pressure-time curve there is a timing wave and an extra baseline. The small secondary pressure peak on the record at about the time when the pressure has first returned to atmospheric pressure is observed on many of the blast records. The cause of this secondary peak is not understood; it is not a reflection. This record illustrates the four exposures which are obtained by rotating the back of the camera; to view calibration steps which were made just before the shot on the left side of the record, the film should be rotated clockwise through 90°.

The precision of measurement of blast pressures and impulses depends on the pressure level at which the measurements are made and on the type of charge being investigated. The scatter is greater at high pressures than at low pressures, probably partly because the shock wave is less uniform at the high pressures. Since the fragments from cased charges produce oscillations which obscure somewhat the pressure-time curve, the precision of measurement of the blast from cased charges is less than the precision obtained when the pressure waves from bare charges are investigated. Between 2 and 25 lb/in.^{2} the standard deviation of a single measurement of peak pressure has been between 2 and 9 percent, and the standard deviation of a single measurement of positive impulse has been between $2\frac{1}{2}$ or 3 percent and 9 or 10 percent. On GP bombs the standard deviations of measurement of peak pressure and positive impulse have been about equal, and vary from 4 percent to 13 percent between 3 and 30 lb/in.^{2}. The lower standard deviations apply at the lower pressures. At pressures as high as 100 lb/in.^{2} the standard deviation of pressure measurements from uncased charges was about 19 percent.

The measurement of peak pressure from determinations of the shock-front propagation velocity are in general more precise than the pressure measurements made directly with gauges.

APPENDIX A

THE DETERMINATION OF PEAK PRESSURE BY MEASUREMENT OF THE SHOCK-FRONT PROPAGATION VELOCITY

The pressure in a shock front may be determined by measuring the speed of propagation of the front in a direction normal to itself. Inasmuch as shock-velocity measurements are not affected by the distortions in the pressure field caused by the interaction of the shock with the measuring devices, pressures determined by this technique are called "true" pressures as distinguished from the pressures measured directly by a pressure-sensitive gauge. Pressure measurements which are determined directly by a gauge are in general affected by the distortion in the pressure field caused by the presence of the gauge in the path of the shock, and consequently do not record the true pressure in the blast wave.

1. Basic considerations

(a) Theoretical foundations. -- The relation between the velocity of propagation and the pressure in a shock wave is obtained from the Rankine-Hugoniot equations and the properties of the medium. The Rankine-Hugoniot equations are based on the conservation of mass, momentum and energy across the shock front [64, 65]. Theoretical tables have been prepared by Brinkley, Kirkwood and Richardson from which the ratio of the shock pressure to atmospheric pressure can be obtained in terms of the ratio of the shock velocity to the speed of sound. These tables were originally reported in Ref. [66]. A corrected table, however, was reported in Ref. [67]. These tables take into account the dissociation of the air, the energy content, and the departures of air from the ideal gas law.

By assuming that the ratio of the specific heat at constant pressure to that at constant volume is a constant across the shock front, and by assuming that air obeys the ideal gas law, it is possible to derive the equation

$$\frac{P_s}{P_o} = \frac{2\gamma}{\gamma+1}\left[\left(\frac{U}{c}\right)^2 - 1\right] \qquad \text{(A-1)}$$

where: P_s = pressure in the shock front in excess of atmospheric pressure

P_o = atmospheric pressure

U = velocity of propagation of shock front

c = speed of sound in undisturbed air

γ = ratio of specific heat at constant pressure to specific heat at constant volume (1.40 for air).

This equation is in good agreement at low pressures with the values calculated by Brinkley, Kirkwood and Richardson, as can be seen from Table A-1. All measurements made at this laboratory have been calculated from Eq. (A-1).

Table A-1. Comparison of theoretical values of shock pressure as a function of shock velocity.

U = velocity of propagation of shock front

c = speed of sound

P_T = pressure in shock front in excess of atmospheric pressure from Kirkwood and Brinkley [67]

P_s = pressure in shock front in excess of atmospheric pressure from Eq. (A-1) for γ = 1.40

Δ = percentage difference between P_T and P_s

U/c	P_T[a] (lb/in.²)	P_s[a] (lb/in.²)	Δ (percent)
1.511	22.05	22.00	0.23
1.998	51.45	51.32	0.25
2.638	102.9	102.2	0.68
3.465	191.1	188.8	1.20
5.414	499.8	485.5	2.86
7.579	1014.3	968.0	4.56

[a] For atmospheric pressure = 14.70 lb/in.²

(b) Outline of experimental techniques. -- To determine the shock pressure P_s in Eq. (A-1) it is necessary to evaluate the shock velocity U, the speed of sound c, and to know the barometric pressure P_o. Since U is the shock velocity relative to the medium, motion of the air (wind), leads to an incorrect measurement of U by stationary indicating devices. Thus the instantaneous wind velocity must also be determined. In addition, inasmuch as the shock velocity is measured over a finite interval, it is necessary to evaluate the distance from the explosion at which the average shock velocity over the interval of measurement is equal to the instantaneous velocity.

The shock velocity is measured by determining the time of arrival of the shock at two points a known distance apart. At this laboratory piezoelectric gauges have been used to indicate the arrival of the shock, but many other types of pressure-sensitive pickups can be employed.

The sound velocity can be evaluated by two different techniques. The simplest method is to determine the velocity of sound from the measurement of air temperature and humidity, but a superior method is actually to measure the speed of a small-amplitude shock wave. The second technique can also be used to determine the wind velocity.

The barometric pressure can be obtained to sufficient accuracy with most types of relatively reliable aneroid barometers.

The precision of measurement of the shock pressure depends on the pressure level, and at low pressures is much less than the precision of measurement of the shock and sound velocities. The fractional error $\frac{\Delta P_s}{P_s}$ in the shock pressure is given by

$$\frac{\Delta P_s}{P_s} = \left(2 + \frac{7}{3}\frac{P_o}{P_s}\right)\left(\frac{\Delta U}{U} - \frac{\Delta c}{c}\right) \qquad \text{(A-2)}$$

where:

$\frac{\Delta P_s}{P_s}$ = fractional error in shock pressure

$\frac{\Delta U}{U}$ = fractional error in shock velocity

$\frac{\Delta c}{c}$ = fractional error in sound velocity

If

$$\Delta = \frac{\Delta U}{U} - \frac{\Delta c}{c} \qquad \text{(A-3)}$$

is independent of the pressure level, then

$$\theta = 2 + \frac{7}{3}\frac{P_o}{P_s} = \frac{\Delta P_s}{P_s} \cdot \frac{1}{\Delta}$$

represents the dependence of the error in the pressure on the pressure level. Values of θ are given in Table A-II.

Table A-II. Error in pressure as a function of pressure level.

P_s = pressure in shock front in excess of atmospheric pressure (atmospheric pressure = 14.7 lb/in.^{2})

θ = relative fractional error in P_s.

P_s (lb/in.^{2})	θ
1	36.2
3	13.1
10	5.4
30	3.1
100	2.3
∞	2.0

Thus, if the error Δ in the determination of the velocity were 0.1 percent, the error in the shock pressure would be 1.3 percent at 3 lb/in.^{2} and 0.2 percent at 100 lb/in.^{2}

2. Measurement of shock velocity

At UERL an average shock velocity $\overline{U}_m$ is measured over an interval Δr. A piezoelectric gauge is placed at each of two distances, r_1 and r_2 ($r_2 > r_1$, $r_2 - r_1 = \Delta r$), from the explosion, and the signal from the gauge is recorded on an oscillograph and rotating-drum camera. The gauges are placed face-on to the blast in order to obtain as short a rise time as possible and the signal is differentiated to reduce the duration of the gauge signal. The duration of the pressure pulse is made short in order to eliminate as many extraneous signals from the trace as possible.

The precision of the determination of $\overline{U}_m$ depends on the measurement of Δr, and on the measurement of the difference in time, on the oscillogram, between the two gauge signals. The gauge signals should have a rapid rise time and, to permit accurate distance measurements, the sensitive portion of the gauge should be thin (parallel to the direction of propagation of the shock wave). The precision of measurement of $\overline{U}_m$ must be greater than the precision which is desired in the shock pressure $\overline{P}_s$, as indicated by Eq. (A-2) and Eq. (A-16).

The distance interval Δr does not need to be known accurately if the gauges used to measure $\overline{U}_m$ are also employed to determine the sound velocity by actual measurement of a small-amplitude shock wave, as discussed in Sec. 3(b). $\overline{U}_m$ is the shock velocity relative to stationary gauges, and must be corrected for the component of the velocity of the wind. (See Sec. 4.)

The value of U which is used in Eq. (A-1) must be the velocity of propagation along a line perpendicular to the shock front, so that a correction must be applied to $\overline{U}_m$ if the distance Δr between the two gauges is not measured along a line parallel to the direction of propagation of the shock wave. A correction of this type has been applied to shock velocity measurements made on the blast from line charges [53].

3. Measurement of the speed of sound

(a) Determination of the speed of sound from the air temperature. -- The speed of sound c' can be obtained from the measurement of the air temperature by the use of the following equation:

$$c' = c_o \left(1 + \frac{t}{273}\right)^{\frac{1}{2}} \qquad \text{(A-4)}$$

where:

c' = speed of sound at temperature t in dry air.
c_o = speed of sound at 0°C in dry air (taken as 1087.1 ft/sec).
t = temperature of air in degrees C.

The speed of sound can be determined within 0.1 percent by measuring the air temperature to 0.5°C, (at 0°C). Reliable air temperatures, in a field exposed to direct sunlight, cannot always be obtained, however.

A correction to the speed of sound calculated from Eq. (A-4) must be made for the humidity of the air. This correction is given in Sec. 5.

(b) Determination of the speed of sound by direct measurement. -- The preferred method of determining the speed of sound is by measuring the average speed of a shock wave of small amplitude, that is, one whose velocity is only slightly greater than that of sound. This can be done readily by using the same gauges that are employed for determining the shock velocity to record the speed of a shock wave from a small charge, such as a detonator cap. A larger charge than a cap can be used at a large distance from the gauges. This technique is used primarily because it permits the determination of the wind velocity. This is discussed in the next section; it is assumed in this section that no wind is present.

At low pressures Eq. (A-1) reduces to

$$\frac{p}{P_o} \approx \frac{4\gamma}{\gamma + 1}\left(\frac{u}{c} - 1\right) = \frac{7}{3}\left(\frac{u}{c} - 1\right) \tag{A-5}$$

where:

- p = pressure in small-amplitude shock wave in excess of atmospheric pressure
- P_o = atmospheric pressure
- u = velocity of propagation of small-amplitude shock front
- c = speed of sound in undisturbed air
- γ = ratio of specific heats (1.40).

By rearranging and expanding, we have:

$$c \approx \frac{u}{1 + \frac{3}{7}\frac{p}{P_o}} \approx u\left(1 - \frac{3}{7}\frac{p}{P_o}\right) \tag{A-6}$$

If p is sufficiently small, an approximate estimate of c can be obtained by applying a small correction to u. An approximate equation for p at pressures of a few tenths of a pound per square inch is:

$$p = 145\left(\frac{W^{1/3}}{r}\right)^{1.41} \tag{A-7}$$

where:

- p = peak pressure (lb/in^2)
- w = charge weight (lb)
- r = distance from charge (ft)

By considering r to be the mean distance from the charge to the two gauges used to measure the velocity of the small-amplitude shock wave, we obtain, by substituting Eq. (A-7) in Eq. (A-6):

$$c \approx u\left[1 - \frac{62.1}{P_o}\left(\frac{W^{1/3}}{r}\right)^{1.41}\right] \tag{A-8}$$

or, if the atmospheric pressure $P_o = 14.7$ lb/in^2,

$$c \cong u \left[1 - 4.23 \left(\frac{W^{1/3}}{r} \right)^{1.41} \right] = u\,(1 - \alpha) \qquad \text{(A-9)}$$

where:

$$\alpha = 4.23 \left(\frac{W^{1/3}}{r} \right)^{1.41}$$

The accuracy of Eq. (A-7) is probably about 30 percent so that, if the pressure is sufficiently low, Eq. (A-9) can be used to obtain reliable sound velocity measurements. For example, if gauges are placed at 20 ft and 30 ft from an Engineers' Special blasting cap, which contains 13.5 grains of PETN, the correction factor $\underline{\alpha}$ in Eq. (A-9) would be about 0.6 percent, and since the uncertainty in the correction is 30 percent, the uncertainty in the sound velocity calculated from this equation would be 0.2 percent. The pressure at the two gauges would be 0.27 lb/in^2 and 0.15 lb/in^2. If more accurate results are to be obtained it is necessary either to record the sound velocity at lower pressures or to obtain a more accurate equation than Eq. (A-7) for the pressure as a function of distance and weight.

Measurements of the speed of sound by this technique have been in good agreement with the sound velocity calculated from measurements of air temperature.

If the same gauges are used to measure the speed of sound that are used to measure the shock velocity, it is unnecessary, in order to determine the pressure, to know the distance between the two gauges in the interval. If the distance between the two gauges used to record the time of arrival of the shock wave is Δr, and if Δt_1 is the time between the arrival of the shock wave at the two gauges and Δt_2 the time between the arrival of the small-amplitude shock wave at the two gauges,

$$\frac{U}{c} = \frac{\dfrac{\Delta r}{\Delta t_1}}{\dfrac{\Delta r}{\Delta t_2}(1 - \alpha)} = \frac{\Delta t_2}{\Delta t_1}\,\frac{1}{1 - \alpha}$$

where $\underline{\alpha}$ is given in Eq. (A-9). Thus, from Eq. (A-1)

$$\frac{P_s}{P_o} = \frac{7}{6} \left[\left(\frac{\Delta t_2}{\Delta t_1}\,\frac{1}{1 - \alpha} \right)^2 - 1 \right]$$

Note that an error in the absolute magnitude of the timing standard is also cancelled out.

4. <u>The effect and measurement of wind velocity</u>

(<u>a</u>) <u>Effect of wind.</u> — The average shock velocity $\overline{U}_m$ measured by stationary gauges represents the true shock-wave velocity only when the air is still, that is, when there is no wind. If there is wind of speed V, the true average shock velocity $\overline{U}$, is given by the vector equation

$$\vec{U} = \vec{U}_m - \vec{V} \qquad \text{(A-10)}$$

where the arrows indicate vector quantities. If the wind were neglected, the fractional error in the pressure $\frac{\Delta P_s}{P_s}$ would be

$$\frac{\Delta P_s}{P_s} \approx \frac{7}{3}\left(\frac{P_o}{P_s}\right)\left(\frac{U}{c}\right)\left(\frac{V}{c}\right) \qquad \text{(A-11)}$$

where $\underline{V}$ is the component of the wind velocity parallel to the direction of propagation of the shock front, and the other notation is the same as above. If the direction of the wind were opposite to the direction of propagation of the shock wave, the calculated pressure would be too low rather than too high. The magnitude of the errors introduced by wind are given in Table A-III.

Table A-III. Effect of wind on pressure.

$\frac{\Delta P_s}{P_s}$ = percentage error in shock pressure

P_s = pressure in shock front in excess of atmospheric pressure

V = component of wind velocity in direction of propagation of shock front

P_s[b] (lb/in²) \ V (mi/hr)	$\frac{\Delta P_s}{P_s}$[a] (percent) 1	3	10	30
1	4.7	14.1	47	141
3	1.6	5.0	16.5	50
10	0.6	1.7	5.8	17
30	0.3	0.8	2.5	7.6
100	0.1	0.4	1.2	3.6

[a] For velocity of sound = 1100 ft/sec.

[b] For atmospheric pressure = 14.7 lb/in².

A determination of the average wind velocity over a long time interval is not, in general, adequate, because local and instantaneous winds are present which cannot be determined by the usual anemometers.

(b) Determination of the instantaneous wind velocity. — The method of measuring wind velocity described in the following is a modification of the technique first used at the Ballistic Research Laboratory [68]. At UERL the component of the wind velocity parallel to the direction of propagation of the primary shock wave is obtained from the measurement of the speed of a small-amplitude shock wave. The technique employed is identical to that described in the previous section except that two detonator caps or small charges are used instead of one. One of these caps is placed at each end of the line of gauges employed for measuring the primary shock velocity and the apparent velocity of the small-amplitude shock waves from each cap is measured. The apparent velocities obtained from the measurement of the small-amplitude shock waves from the blasting caps, corrected for the finite amplitude of the shock, are the vector sum of the wind velocity and the true sound velocity, so that the component of the wind velocity along the line of gauges is one-half the difference between the corrected apparent shock velocities from the two blasting caps and the true sound velocity is the average of these two corrected apparent velocities. The two caps are detonated one or two seconds before the charge is detonated and thus it is possible to obtain a fairly good approximation of the actual wind conditions at the time the shock wave from the charge is recorded.

The technique employed does not determine the component of the wind velocity perpendicular to the line of gauges, but this component has a negligible effect, as can be seen from the following considerations. The apparent velocity of the small-amplitude shock wave from a blasting cap located at that end of the line of gauges which is nearest the charge is given by

$$u_1 = \frac{u^2 - V^2}{-V \cos \phi \pm \sqrt{u^2 - V^2 \sin^2 \phi}} \qquad \text{(A-12)}$$

where:

u_1 = apparent velocity of the small-amplitude shock wave from blasting cap at that end of line of gauges which is nearest the charge

u = true velocity of small-amplitude shock wave

V = wind velocity

ϕ = angle between direction of wind and line from charge through line of gauges.

The apparent velocity of the small-amplitude shock wave from the blasting cap located at that end of the line of gauges which is farthest from the charge, u_2, is given by

$$u_2 = \frac{u^2 - V^2}{V \cos \phi \pm \sqrt{u^2 - V^2 \sin \phi}} \qquad \text{(A-13)}$$

These equations are derived on the assumption that u is a constant. The component of the wind velocity parallel to the direction of propagation of the primary shock wave is given by one-half the difference between the two apparent velocities of the small-amplitude shock waves,

$$V \cos \phi = \frac{u_1 - u_2}{2} \tag{A-14}$$

The true velocity of the small-amplitude shock wave is given by the average of the two velocities,

$$u = \frac{u_1 + u_2}{2} \frac{1}{\sqrt{1 - \left(\frac{V}{u}\right)^2 \sin^2 \phi}} \approx \frac{u_1 + u_2}{2} \left[1 + \frac{1}{2}\left(\frac{V}{u}\right)^2 \sin^2 \phi\right] \tag{A-15}$$

If $\phi = 0$, that is, if the wind is parallel to the direction of propagation of the shock wave,

$$V = \frac{u_1 - u_2}{2}$$

and

$$u = \frac{u_1 + u_2}{2}$$

so that the true values of the component of the wind velocity and the small-amplitude shock velocity are obtained. If $\phi = \frac{\pi}{2}$, that is, if the wind is perpendicular to the direction of propagation of the shock wave,

$$u_1 = u_2, \text{ V indeterminate}$$

and

$$u = \frac{u_1 + u_2}{2} \left[1 + \frac{1}{2}\left(\frac{V}{u}\right)^2\right]$$

Thus the value of the small-amplitude shock velocity determined by this technique is in error by the amount $\frac{1}{2}\left(\frac{V}{u}\right)^2$. This quantity, however, is equal to only 0.0008 when V is equal to 30 mi/hr. For most practical purposes, since a wind with a component of velocity equal to 30 mi/hr perpendicular to the line of gauges is not encountered ordinarily, the correction will be less than 0.08 percent, and consequently can be neglected. When a strong wind is present, it is possible to obtain the direction of the wind with a weather vane and thus a correction can be applied to the small amplitude shock velocity by the use of Eq. (A-15) provided that the wind is not directly perpendicular to the line of gauges.

Equation (A-15) also indicates that the component of the wind perpendicular to the direction of propagation of the shock wave has a negligible effect on the measurement of the shock velocity from the charge.

The correction for the finite amplitude of the shock wave from the blasting caps can be applied to the individual small-amplitude-shock-wave velocities u_1 and u_2 or, when the corrections to the two individual velocities are about equal, to the average velocity, $\underline{u}$.

When the wind and sound velocities are determined by the above technique, the error in the shock pressure is given by [see Eq. (A-2)],

$$\frac{\Delta P_s}{P_s} = \Theta\left[\frac{\Delta U}{U} - \frac{\Delta c}{c}\left(1 + \frac{c}{U}\right)\right] \qquad \text{(A-16)}$$

Since the interval between the gauges used to record the time of arrival of the shock wave cancels out of Eq. (A-1), as pointed out in Sec. 3(b), the only errors involved in $\underline{U}$ and $\underline{c}$ are those encountered in measuring the oscillogram.

5. The effect of humidity

Shock pressures determined by the measurement of the shock-wave propagation velocity are affected by humidity both because the ratio of specific heats, γ, and the speed of sound depend on the presence of water vapor in the air. Since the affect of humidity on the speed of sound is included in the determination of the sonic velocity from the measurement of the velocity of a small-amplitude shock wave, the effect of humidity on the speed of sound is of importance only when the speed of sound is determined by the measurement of air temperature.

When the speed of sound is determined by the measurement of the velocity of a small-amplitude shock wave, humidity affects the calculated pressure only through γ in the factor $\frac{2\gamma}{\gamma + 1}$ in Eq. (A-1). The error $\frac{\Delta P_s}{P_s}$ in the shock pressure due to a change in γ is given by

$$\frac{\Delta P_s}{P_s} = \frac{1}{\gamma + 1}\frac{\Delta\gamma}{\gamma} = 0.42\,\frac{\Delta\gamma}{\gamma} \qquad \text{(A-17)}$$

where:

$\frac{\Delta P_s}{P_s}$ = fractional change in shock pressure due to a change in γ

$\frac{\Delta\gamma}{\gamma}$ = fractional change in the ratio of specific heats

The dependence of γ on the presence of water vapor is given approximately by [44]

$$\gamma = \gamma_a\left[1 + \left(\frac{\gamma_a - 1}{\gamma_w - 1}\right)\left(\frac{\gamma_w}{\gamma_a} - 1\right)\frac{P_w}{P_a}\right] \qquad \text{(A-18)}$$

where:

γ = ratio of specific heats of air in moist air
γ_a = ratio of specific heats of air in dry air
γ_w = ratio of specific heats of water vapor
P_w = partial pressure of water vapor
P_a = partial pressure of air

At 100 percent humidity at 30°C the correction to γ_a is about 0.3 percent. From Eq. (A-17) it is seen that the maximum error in the shock pressure due to humidity, for temperatures below 30°C, is 0.13 percent, and consequently humidity has an entirely negligible effect when the speed of sound is determined by velocity measurements.

The variation of the speed of sound with humidity is given approximately by [44]

$$c = c' \left(1 + 0.149 \frac{P_w}{P_a}\right) \qquad \text{(A-19)}$$

where:

c = speed of sound in moist air
c' = speed of sound in dry air from Eq. (A-4)
P_w = partial pressure of water vapor
P_a = partial pressure of air

At 100 percent humidity at 30°C the correction to the speed of sound is about 0.66 percent. From Eq. (A-2) it is seen that humidity can have an appreciable effect on the determination of the shock pressure when the speed of sound is determined from the measurement of air temperature, and consequently when this method of obtaining the speed of sound is employed, the humidity of the air as well as the temperature must be recorded.

6. <u>Determination of the distance from the explosion at which the average shock velocity measured is equal to the instantaneous shock velocity</u>

The shock velocity determined experimentally is an average value over the interval Δr between the gauges used to record the time of arrival of the shock. In order to determine the distance at which the pressure calculated from Eq. (A-1) is to apply, it is necessary to find the distance from the explosion at which this average velocity is equal to the instantaneous shock velocity. The equations for determining this distance will be derived in the following.

The instantaneous shock velocity U is given by

$$U(t) = \frac{dr}{dt}, \qquad \text{(A-20)}$$

where r is the distance from the explosion and t is the time. The measured shock velocity $\overline{U}$ (corrected for wind) is the value of U averaged over time t_1 between the arrival of the shock at the first gauge used to record the arrival of the shock and the time t_2 of the arrival of the shock at the second gauge. This average shock velocity is given by

$$\overline{U} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} U(t)\, dt = \frac{r(t_2) - r(t_1)}{t_2 - t_1} \qquad \text{(A-21)}$$

At a time τ intermediate between t_1 and t_2 the instantaneous velocity $U(t)$ is equal to

$$U(\tau) = \frac{r(t_2) - r(t_1)}{t_2 - t_1} = \overline{U} \qquad t_1 \leq \tau \leq t_2 \qquad \text{(A-22)}$$

That is, at the time τ, the instantaneous velocity is equal to the average velocity over the interval. Since the distance from the charge r is a function of time, $r = r(t)$, there is a particular r, $r = R_v$, for which $R_v = r(\tau)$. R_v is the distance from the explosion at which the instantaneous shock velocity is equal to the average shock velocity measured over the interval between the two gauges used to record the arrival of the shock. It is the distance from the explosion at which the pressures calculated from Eq. (A-1) apply.

The method of calculating R_v depends on the use of an expression for the decay of shock velocity with distance. Since such an expression is not usually known before the shock velocities have been measured and R_v calculated, it is necessary to obtain the expression for the decay of velocity with distance by successive approximations. It is thus necessary to measure shock velocities over at least two close intervals. For an example of the calculation of R_v by successive approximations, see Ref. 53. As a rule the decay of peak pressure with distance is more likely to be known than the decay of velocity with distance, so that it is the procedure at this laboratory, following the technique used by the Ballistic Research Laboratory [17], to use the decay of pressure with distance as a basis for calculating R_v. The relation between pressure and velocity is obtained from Eq. (A-1)

Since at $r = R_v$, $U = \overline{U}$, Eq. (A-1) becomes

$$P_s(R_v) = \frac{7P_o}{6}\left[\left(\frac{U(R_v)}{c}\right)^2 - 1\right]$$
$$= \frac{7P_o}{6}\left[\left(\frac{\overline{U}}{c}\right)^2 - 1\right] \qquad \text{(A-23)}$$

By obtaining the function $P_s(R_v)$ and solving for R_v, the latter can be calculated from this equation. In order to obtain an analytical expression for $\overline{U}$, it is necessary to determine the time over which $\overline{U}$ is measured in terms of r. Since, from Eq. (A-20)

$$dt = \frac{dr}{U(r)},$$

$$t_2 - t_1 = \int_{t_1}^{t_2} dt = \int_{r_1}^{r_2} \frac{dr}{U(r)} \qquad \text{(A-24)}$$

where $r_1 = r(t_1)$ and $r_2 = r(t_2)$ are the distances from the explosion of the two gauges used to record the time of arrival of the shock wave. Rearranging Eq. (A-1) we obtain

$$U(r) = c\left[\frac{6}{7}\frac{P_s(r)}{P_o} + 1\right]^{\frac{1}{2}}, \qquad \text{(A-25)}$$

so that, on substituting this equation in Eq. (A-24), we have

$$t_2 - t_1 = \int_{r_1}^{r_2} \frac{1}{c}\left[\frac{6}{7}\frac{P_s(r)}{P_o} + 1\right]^{-\frac{1}{2}} dr \qquad \text{(A-26)}$$

Substituting the value of $t_2 - t_1$ from this equation in Eq. (A-21) and letting $r(t_2) - r(t_1) = \Delta r$, we obtain

$$\overline{U} = \frac{\Delta r}{\int_{r_1}^{r_2} \frac{1}{c}\left[\frac{6}{7}\frac{P_s(r)}{P_o} + 1\right]^{-\frac{1}{2}} dr} \qquad \text{(A-27)}$$

If, for example, the dependence of P_s on distance can be represented by the equation

$$P_s(r) = A\,r^{-n} \qquad \text{(A-28).}$$

where A and n are constants [see Eq. (0.1) in the Introduction], we obtain, by combining Eqs. (A-23), (A-27), and (A-28), and solving for R_v,

$$R_v = \left\{\frac{1}{k}\left[\left(\frac{\Delta r}{J}\right)^2 - 1\right]\right\}^{-1/n} \qquad \text{(A-29)}$$

where:

R_v = distance from explosion at which average shock velocity measured over interval Δr is equal to instantaneous shock velocity

$\Delta r = r_2 - r_1$

r_1, r_2 = distance from explosion to two gauges used to record the time of arrival of the shock wave $(r_2 > r_1)$

$$J = \int_{r_1}^{r_2} (1 + kr^{-n})^{-\frac{1}{2}} \, dr \qquad \text{(A-30)}$$

$$k = \frac{6A}{7P_o}$$

P_o = atmospheric pressure

A, n = constants in $P_s(r) = A r^{-n}$, when $P_s(r)$ is peak pressure in excess of atmospheric pressure

The validity of Eq. (A-29) is limited by Eq. (A-28). The largest interval (defined by r_1 and r_2) which can be used is that interval for which the decay of pressure with distance can be represented by a straight line on a logarithmic plot. This restriction has not been a limitation in practice.

The integral J in Eq. (A-30) cannot be evaluated by exact methods, but two approximate formulas can be obtained, one of which applies at high pressures and one at low pressures. In the intermediate region, it is necessary to resort to a procedure of numerical integration.

Case I. $P_s < 17$ lb/in^2.

In this case, in which the interval Δr is at pressures entirely below 17 lb/in^2, $k r^{-n} < 1$. On expanding the integrand in Eq. (A-30) and integrating we obtain:

$$J = \Delta r + \sum_{\nu=1}^{\infty} (-k)^{\nu} \frac{(2\nu - 1)!\nu}{2^{(2\nu-1)}(\nu!)^2} \frac{1}{1 - n\nu} \left[r_2^{(1-n\nu)} - r_1^{(1-n\nu)} \right] \qquad \text{(A-31)}$$

Letting:

$R_m = \frac{1}{2}(r_1 + r_2)$ = mean distance from explosion to interval Δr

$$q = \frac{r_2 - r_1}{R_m},$$

and expanding in q the following equation is obtained:

$$J \cong q R_m + \sum_{\nu=1}^{\infty} (-k)^{\nu} \frac{(2\nu - 1)!\nu}{2^{(2\nu-1)}(\nu!)^2} q R_m^{(1-n\nu)} \left[1 + \frac{(n\nu)(1+n\nu)}{6} \left(\frac{q}{2}\right)^2 \right]$$

where powers of q greater than the fourth have been dropped.

Substituting this equation in Eq. (A-29) and expanding, dropping powers greater than the first (except in q), we obtain for R_v,

$$R_v = R_m \left[1 - \left(\frac{n+1}{24} \right) q^2 \right] \tag{A-32}$$

This equation was first reported by the Ballistic Research Laboratory [17]. It applies for $P_s < 17$ lb/in.² and for $q < 2$.

Case II. $P_s > 17$ lb/in.²

In this case, in which the interval Δr is at pressures entirely above 17 lb/in.², $k\, r^{-n} > 1$. By rearranging the integrand in Eq. (A-30) and expanding, an equation similar to Eq. (A-31) is obtained. By an analagous procedure to that used to obtain Eq. (A-32), the following equation for R_v can be found:

$$R_v = R_m \left\{ 1 - \frac{q^2 R_m^n}{16K} \left[\frac{3n-2}{2} + \left(\frac{2-n}{3} \right) \frac{k}{R_m^n} \right] \right\} \tag{A-33}$$

This equation applies for $P_s > 17$ lb/in.² and for $q < 2$.

APPENDIX B.

DESIGN AND TESTING OF ELECTRONIC CIRCUITS

Certain of the details of the amplifier circuits and trigger circuits used in UERL equipment are discussed in this appendix. The techniques used for testing response characteristics are also described.

1. Component circuits of UERL amplifiers

(a) High resistance input. -- The high input resistance required in the first stage of amplifiers for use in piezoelectric gauge circuits has been obtained at UERL by two different methods. In one type of circuit a large grid resistor is used and in the other a comparatively small grid resistor is employed in an arrangement to give a large effective input resistance.

(i) Input circuit with large grid resistor. An input circuit of the large grid resistor type is shown schematically in Fig. 48a. The grid resistor R_g is usually 500 to 1000 megohms. As minute amounts of grid current will cause considerable voltage to develop across the grid resistor, it is necessary to reduce grid current as much as possible, which is done by using low plate and screen voltages and a high negative grid bias. A large negative supply voltage is employed so that a large cathode resistor R_c can be used, making the stage highly degenerative. The best circuit parameters and tubes to be used in this circuit have not been determined, but the values given in the circuits in Chap. 5 for 6J7 tubes, have been found to be satisfactory. The tubes must be selected, however, for grid current and microphonics. It is necessary to use DC for the heaters in this stage in order to avoid AC hum in the output. The pickup of AC hum is emphasized by the large grid resistor.

It is usually necessary to employ direct coupling between amplifier stages wherever possible, so as to maintain an adequate low-frequency response. Since the grid of the circuit in Fig. 48a is connected to ground, and the stage is highly degenerative, the output of this circuit is relatively free from drift and is thus well adapted to direct coupling.

The condenser C is required to insure that the DC grid impedance will be independent of the circuit connected across the input. The time constant R_gC of this circuit is made about one hundred times the longest time to be measured and does not introduce additional errors in the measurement of positive impulse.

(ii) High resistance input with small grid resistor. An input circuit which uses a small grid resistor is shown in Fig. 48b. If this circuit is analyzed it is found that the input resistance Z_i is given by

$$Z_i = R_g \frac{1}{1 - \frac{R_2}{R_c} a} \qquad \text{(B-1)}$$

where $R_c = R_1 + R_2$ and where a, the gain of the stage, is given by

$$a = \frac{\mu R_c}{r_p + (1+\mu) R_c} = \frac{g_m r}{1 + g_m r} \qquad \text{(B-2)}$$

where μ, r_p, and $g_m = \mu/r_p$ are the amplification factor, plate resistance and transconductance of the tube respectively, $R_c = R_1 + R_2$ and $r = r_p R_c/(r_p + R_c)$. If $R_1 = 0$, if a bias battery is placed in series with the grid, and if $R_c >> r_p$,

$$Z_1 = R_g (1 + \mu) \qquad \text{(B-3)}$$

so that Z_1 can be made considerably larger than R_g. It is important to note that, for a pentode, unless the screen circuit is completely by-passed to the cathode, the value which must be used for r_p in the above equations is the dynamic resistance of the screen circuit. Thus, unless the screen is by-passed to the cathode, a pentode functions like its equivalent triode. Since a condenser in the screen circuit introduces low-frequency attenuation, screen by-passing is best accomplished by means of a battery or VR tube connected between the screen and cathode. Using a 6J7 tube it was found that the input resistance obtained for values of Z_1 up to 75 megohms was approximately equal to that calculated from the above equations, but that above 75 megohms the actual Z_1 was lower than the calculated value. The discrepancy was attributed to leakage in the tube; attaching the tube shield to the cathode rather than to ground increased Z_1 somewhat. This type of input is not well adapted to direct coupling to the following stage because the cathode voltage, which is determined by the bias resistor or battery, the cathode resistor, and the tube characteristics, is quite susceptible to drift.

(b) Methods of coupling between stages. — The stages of wide-band amplifiers are usually connected together by either direct coupling or by resistance-capacitance coupling. Direct coupling is advantageous because it does not attenuate the low frequencies, but serious difficulties are encountered when direct-coupling is used in high-gain amplifiers because drift in an early stage of the amplifiers disturbs the operating conditions of the later stages. Under field conditions the drift can be very troublesome. Although drift is not a difficulty in resistance-capacitance coupling, this type of coupling causes low-frequency attenuation [see Sec. 5.1(c)]. In order to make the attentuation small, a long time constant is required. Time constants of more than 1 sec are difficult to obtain because the maximum usable size of both the coupling condenser and grid resistor is limited. In large condensers the limiting factor is leakage current, and large resistors cannot be used because of the voltage developed across them by condenser leakage current and grid current.

Low-frequency compensation is used at UERL to obtain long time-constants on inter-stage coupling networks. In this method (see Fig. 49) the decaying exponential of the coupling circuit is counteracted by a rising exponential in the plate circuit. In the limiting case of R_C infinitely large (Fig. 49) $R_gC_g = R_LC_C$ and the response of the circuit to an input step wave is also a step. For finite values of R_C the output response is intermediate to a step and to the exponential decay of the uncompensated stage. By making R_gC_g greater than R_LC_C the response is overcompensated, that is, the response at low frequencies rises above that at intermediate frequencies. The response of this circuit to a unit step has been worked out by Lampson [63]. The result of this computation is:

$$F(t) = g_m R_L \left[\frac{(\delta + \beta - \gamma)\, e^{-\gamma t} - \delta e^{-\beta t}}{\beta - \gamma} \right] \qquad \text{(B-4)}$$

where: (see Fig. 49)

t = time after application of the step

$$\beta = \frac{1}{R_C\, C_C}$$

$$\delta = \frac{1}{R_L\, C_C}$$

$$\gamma = \frac{1}{R_g\, C_g}$$

and where it is assumed that

$$\frac{R_L}{R_g} << 1$$

$$\frac{R_C}{R_g} << 1$$

(c) Applications of balanced circuits. — Push-pull amplifier circuits are useful in many parts of the equipment employed in air-blast measurements. They are useful because: (1) in-phase components of the input signal are not present in the output, (2) a considerable amount of power-supply fluctuation is eliminated, (3) second harmonic distortions are cancelled out, (4) a balanced signal is desirable for deflection of the trace on cathode-ray tubes, (5) a useful method of gain control is adapted only to push-pull circuits, and (6) the degenerative action of screen and cathode impedances can be eliminated without introducing frequency dependent impedances.

An important application of a balanced circuit is the conversion from a push-pull input to single-ended output. This type of circuit is used in the preamplifiers described in Chap. 5. In this circuit it is necessary to obtain a single-ended output which, like the output of an ordinary push-pull stage, does not contain any components of an in-phase signal applied to the input. The equations which govern the design of this type of stage are given in the following. Reference should be made to second stage of the circuit in Fig. 5.

If the signals applied to the two tubes T_1 and T_2 in any push-pull stage are e_1 and e_2 respectively, both signals being considered positive, the output voltages E_1 and E_2 of T_1 and T_2, respectively, are given by

$$E_1 = -\frac{a}{2}\left[(e_1 - e_2) + \eta(e_1 + e_2)\right] \qquad \text{(B-5)}$$

$$E_2 = \frac{a}{2}\left[(e_1 - e_2) - \eta(e_1 + e_2)\right] \qquad \text{(B-6)}$$

where

$$a = \frac{g_m R_L}{1 + g_m R_C} \qquad \text{(B-7)}$$

is the gain of single-ended stage with load resistor R_L, cathode resistor R_C, and transconductance g_m and where it is assumed that the amplification factor $\mu >> 1$, the plate resistance $r_p >> R_L$ and where

$$\eta = \frac{1 + g_m R_C}{1 + g_m (R_C + 2R)} \qquad \text{(B-8)}$$

If $e_1 = \frac{1}{2}(e - \alpha e)$ and $e_2 = -\frac{1}{2}(e - \alpha e)$, that is, where both grids are excited with an out-of-phase signal of amplitude $\underline{e/2}$ and an in-phase signal $\underline{\alpha e/2}$,

$$E_1 = -\frac{ae}{2}(1 + \alpha\eta) \qquad \text{(B-9)}$$

$$E_2 = \frac{ae}{2}(1 - \alpha\eta) \qquad \text{(B-10)}$$

The total output voltage $\underline{E}$ between the two tubes is the difference between E_1 and E_2, that is

$$E = E_1 - E_2 = -a\,e, \qquad \text{(B-11)}$$

which is the output from the equivalent single-ended stage with net grid signal, and no in-phase signal. Thus, although the in-phase signal is excluded from the output of the two tubes taken together, it appears in the output of the two separate tubes. If, for a given α, η is made small, the output of the separate tubes contains only a small amount of the in-phase signal. The quantity η may be considered to represent the amount of transfer from one tube to the other. For $\eta = 1$ the transfer is a minimum and the output contains all of the in-phase signal; if $\eta = 0$ the transfer is a maximum and all the in-phase signal in the output is cancelled so that, as far as response to the input signal is concerned, the output is equivalent to half the magnitude of the output of the two tubes taken together. If there is a screen resistor common to the two tubes, the transfer is greater than indicated by the above equations. If there are individual screen and cathode resistors in each tube, the gain and the transfer will be less.

(d) Output circuits. -- Cathode followers are usually used in the output stage because of the advantages of having a low output impedance.

It is important to note that: (1) the maximum undistorted voltage from a cathode follower is always less than the zero signal cathode voltage, (2) distortion at high frequencies occurs at smaller amplitudes for a capacitative load than for a resistive load. The increased distortion at high frequencies is caused by phase shift between the grid and cathode that is introduced by the capacity. The extent of this effect is best determined empirically.

2. Trigger circuits

Trigger and flip-flop circuits have been used to a considerable extent in sweep-generators, beam-brighteners, time-delays and timing devices. A number of adequate treatments of these circuits are available [35, 5, 15].

Trigger circuits can be constructed from gas tubes (thyratrons) or hard tubes. Both types are well adapted to trigger circuits, but flip-flops (which are trigger circuits with only one stable position) using thyratrons have been found to be less reliable and more difficult to adjust than hard-tube circuits.

Two different types of flip-flop circuits are used at UERL: (1) The Eccles-Jordan type, which is used in the circuits shown in Figs. 11 and 13 [5]. (2) The Schmidt type, which is used in the circuits shown in Figs. 12 and 14 [35]. Eccles-Jordan trigger circuits are used in the circuit shown in Fig. 28. The Schmidt type circuit requires fewer circuit components than the Eccles-Jordan circuit.

In beam-brightener circuits the shape of the output pulse from the flip-flop is of considerable importance because it determines the constancy of the beam-brightening signal. Although in Eccles-Jordan type circuits it has been found that only the tube which is conducting when the circuit is tripped has a pulse with a relatively flat top, in the Schmidt type circuit both tubes give a pulse with a flat top.

It should be noted that the reset time of a flip-flop circuit is not reliable unless the time constant of the input coupling circuit is small compared to the reset time. The input-coupling-circuit time constant should also be small compared to the time between successive cycles of a continuously tripped trigger circuit.

3. Testing of equipment

(a) Frequency response. — Although the conventional type of signals used for testing frequency response are sine waves and square waves, these signals are not completely satisfactory for testing the response of equipment to be used for recording transient phenomena. In general, steady state signals are unsatisfactory because the operating point of an amplifier stage under steady state conditions may be different from the operating point when no signal is applied. Thus, in the last analysis, transient signals should be employed for determining the response of equipment for use in blast measurements. For general testing it is more convenient, however, to use steady state signals than it is to use transient signals, so that, except for determining the low-frequency response, sinusoidal signals are used for preliminary testing. At frequencies below 20 cps sinusoidal signals are difficult to use and commercial square wave generators do not usually have a sufficiently slow repetition rate.

(i) Measurement of high-frequency response. Two methods of measuring the high-frequency response of an amplifier are in use at UERL. One method involves the use of a variable oscillator and a vacuum tube voltmeter. It should be noted that measurements of frequency response made with constant output voltage for different frequencies may result in a different response curve from that obtained if the change in output voltage with frequency were measured at fixed input voltages.

Another method, which is useful for oscillograph amplifiers used for transient recording, consists of applying exponentials of different time constants to the amplifier. This method is described in Ref. 33.

(ii) Measurement of low-frequency response. Measurements of low-frequency response are made by determining the time constant of the circuit on a cathode-ray oscillograph; the time constant is determined from a photograph of the oscillogram when accurate results are required. For a unit-step input the decay of the output pulse at the time corresponding to the duration of the signals for which the amplifier is to be used represents the useful response better than a measurement of the time constant, because: (1) in a multi-stage amplifier there is a superposition of exponentials, and (2) in a properly compensated amplifier there is less decay in the initial portion of the step than would be implied by a measurement of the time constan In this usage, the term "time constant" means the time at which the step-response of an amplifier has decayed to $\frac{1}{e}$ (e = 2.718) times its initial value.

(iii) Measurement of input resistance. Measurement of the input resistance can be accomplished with the circuit of Fig. 50. A step is applied to the circuit to be tested, shown as Z in the figure, through the condenser C_t

and the output is observed on a cathode-ray oscillograph. The measurement of the time constant of the input circuit, which is C_tZ_1, can be determined if C_tZ_1 is small compared to the other time constants in the oscillograph. This method is not satisfactory if the input resistance varies with time, as would be the case if the screen circuit were by-passed. In that case C_tZ_1 must be made large enough to cover the maximum time to be recorded.

(b) Equivalent gauge circuits for testing response. — The equivalent circuit of a piezoelectric gauge at frequencies well below its natural frequency is a condenser in series with a voltage generator of zero impedance [8]. An equivalent gauge circuit is used for testing gauge cables and termination [26]. The series condenser should be equal to the actual capacity of the gauge elements, and the voltage source should have an internal impedance that is low compared to the impedance of the condenser at the highest frequencies of importance. The condensers used are usually 100 $\mu\mu$f, which, although larger than the internal capacity of small gauges, will not introduce an error at the highest frequencies ordinarily considered. For measurements at low frequencies the DC leakage resistance of this condenser should be very high [see Sec. 9.2(c)] and the dielectric absorption should be low. The voltage source used is either a step-generator using a low-impedance voltage circuit or a low-impedance-output cathode follower which can be used for coupling an oscillator or a step-generator to the series condensers.

(c) Simulated pressure signal for testing response. — Occasionally it is desirable to apply a signal to the cables or amplifiers with a wave form roughly equivalent to a pressure wave. A circuit for this purpose is presented in Ref. 9.

(d) Linearity. — The linearity of the recording system can be affected by the amplifier, cathode-ray tubes and photographic equipment. Usually an over-all check of linearity is made by comparing the deflections of photographs of steps of different size. This is tedious and not very accurate because: (1) the reproducibility of the steps is of the same order of magnitude as the non-linearities ordinarily encountered, and (2) it is difficult to measure the small steps accurately. A vacuum-tube voltmeter which has been calibrated for linearity can be used for testing amplifiers alone.

APPENDIX C

EQUATIONS FOR THE CHARGE CALIBRATION STEP IN PUSH-PULL SYSTEMS

Two different push-pull gauges are used: Type 1, in which none of the gauge electrodes are grounded, and Type 2, in which the center of the gauge is grounded. When the charge-calibration step is used with these circuits, shown in Figs. 26 and 27, the equation given below can be used to calculate the pressure. The approximate equation given in Chap. 9, Eq. (9.14) is ordinarily of sufficient accuracy, but in cases where there is considerable unbalance on the two sides of the push-pull circuit, the exact equations are used for the purpose of supplying a correction to the approximate equation. It is, of course, necessary to measure all the parameters involved in the exact equations, but small changes in these parameters between the time they are measured and the time that the charge-calibration step is used for blast measurements will not appreciably affect the results.

The notation used in the following equations applies to Figs. 26 and 27, Chap. 9. The exact equations are:

Type 1. Push-pull gauge (Fig. 26):

$$P = \left(\frac{\bar{C}_S V_S}{2(KA)}\right)\left(\frac{d_p}{d_c}\right)(1 + \gamma\theta) \qquad \text{(A)}$$

Type 2. Push-pull gauge (Fig. 27):

$$P = \left(\frac{\bar{C}_S V_S}{2(\overline{KA})}\right)\left(\frac{d_p}{d_c}\right)(1 + \gamma\theta) \qquad \text{(B)}$$

where:

P = peak pressure on gauge

d_p = deflection (on film) of pressure signal

d_c = deflection (on film) of calibration step

$\bar{C}_S = \frac{1}{2}(C_{S1} + C_{S2})$ = mean value of standard condensers

C_{S1} = standard condenser, pin 1

C_{S2} = standard condenser, pin 2

$\gamma = \dfrac{C_{S1} - C_{S2}}{C_{S1} + C_{S2}}$ = fractional unbalance of two standard condensers

$V_S = V_{S1} + V_{S2}$ = total calibration voltage

V_{S1} = standard voltage, pin 1

V_{S2} = standard voltage, pin 2

$$\theta = \frac{V_{S1} - V_{S2}}{V_{S1} + V_{S2}}$$ = fractional unbalance of two sides of voltage divider

(KA) = gauge calibration constant, Type 1 push-pull gauge

$$(\overline{KA}) = \tfrac{1}{2}\left[(KA)_1 + (KA)_2\right]$$ = mean value of gauge calibration constant, both sides of gauge, Type 2 push-pull gauge

$(KA)_1$ = gauge calibration constant, pin 1

$(KA)_2$ = gauge calibration constant, pin 2

$$A = \frac{1 - \delta x - \eta\left[x - \delta\left(1 + \dfrac{2C_3}{\overline{C} + \overline{C}_S}\right)\right]}{1 - \eta x}$$

$$B = \frac{1 - \delta x - \eta\left[x - \delta\left(1 + \dfrac{2C_3}{\overline{C} + \overline{C}_S}\right)\right]}{1 - \varepsilon x - \eta\left[x - \varepsilon\left(1 + \dfrac{2C_3}{\overline{C} + \overline{C}_S}\right)\right]}$$

$$\delta = \frac{2(\theta + \gamma)}{1 + \gamma\theta} = \frac{C_{S1}V_{S1} - C_{S2}V_{S2}}{C_{S1}V_{S1} + C_{S2}V_{S2}}$$ = fractional unbalance of standard charge on two sides of circuit

$$x = \frac{\phi\,\overline{C} + \gamma\,\overline{C}_S}{\overline{C} + \overline{C}_S}$$

$$\overline{C} = \tfrac{1}{2}(C_1 + C_2)$$ = mean value of capacity on two sides of cable

C_1 = cable capacity, pin 1 to ground, not including capacity between conductors

C_2 = cable capacity, pin 2 to ground, not including capacity between conductors

$$\phi = \frac{C_1 - C_2}{C_1 + C_2}$$ = fractional unbalance of two sides of cable

$$\eta = \frac{\alpha - \beta}{\alpha + \beta}$$ = fractional unbalance of deflection sensitivity on two sides of recording equipment

deflection sensitivity = deflection on film per unit voltage on input of amplifier

α = deflection sensitivity, pin 1 to ground

β = deflection sensitivity, pin 2 to ground

C_3 = cable capacity, pin 1 to pin 2, not including capacity to ground

$\epsilon = \dfrac{(KA)_1 - (KA)_2}{(KA)_1 + (KA)_2}$ = fractional unbalance in gauge sensitivity on two sides of circuit (Type 2 gauge only)

Units:

Pressure is in lb/in^2.

Capacitance is in $\mu\mu f$

Voltage is in volts

Gauge calibration constants are in $\mu\mu$coulomb/(lb/in^2.)

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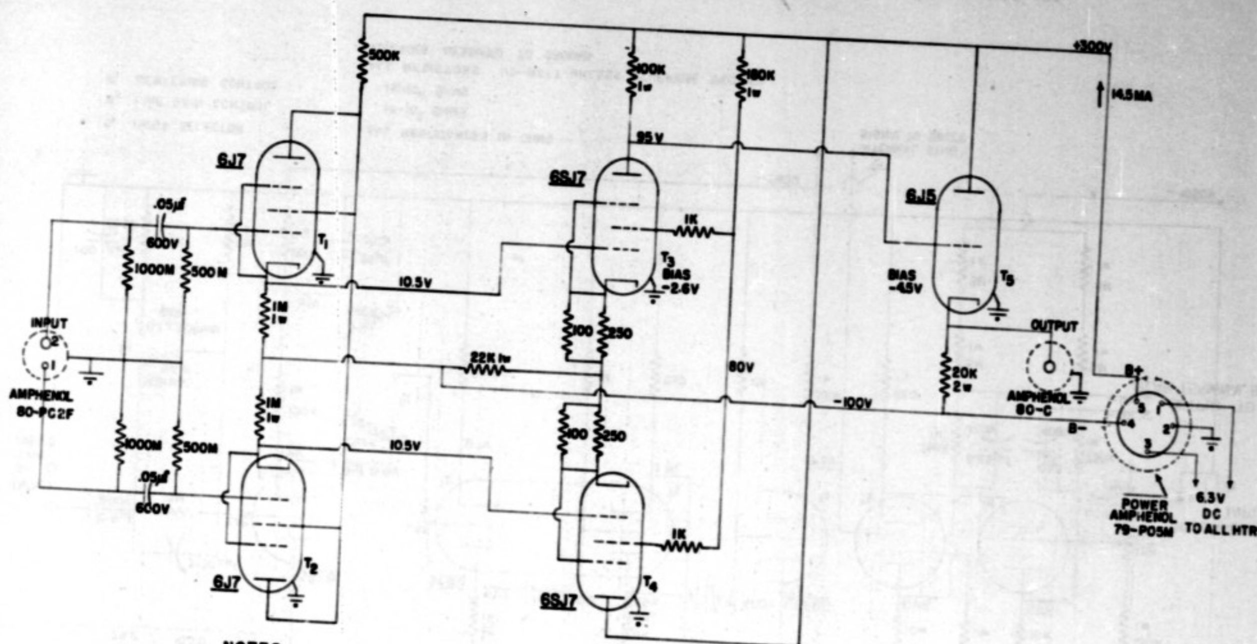
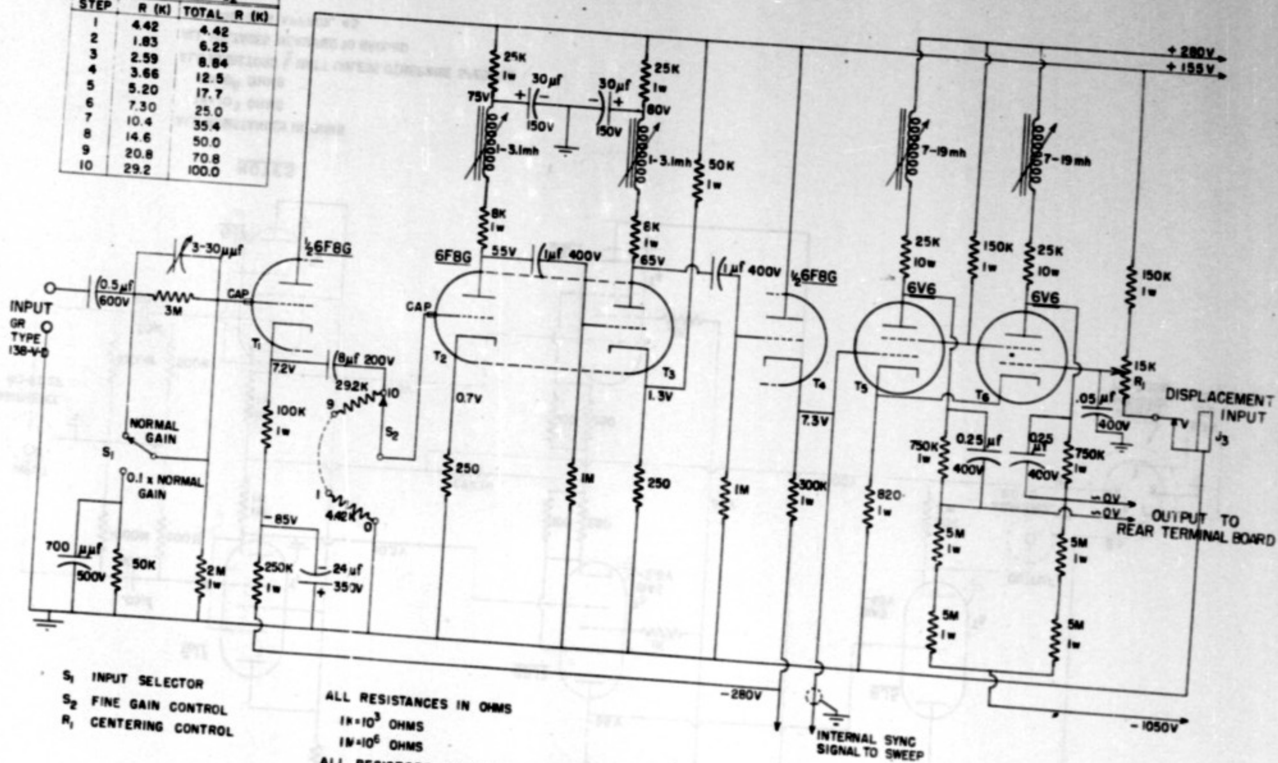


NOTES

ALL RESISTANCES IN OHMS
1K = 10^3 OHMS
1M = 10^6 OHMS
ALL RESISTORS ½ WATT UNLESS OTHERWISE SPECIFIED
ALL VOLTAGES MEASURED TO GROUND
VOLTAGE GAIN APPROX. 45

FIG. 4. PREAMPLIFIER FOR USE WITH DU MONT CATHODE-RAY OSCILLOGRAPH TYPE 208.

RESISTORS IN S_2		
STEP	R (K)	TOTAL R (K)
1	4.42	4.42
2	1.83	6.25
3	2.59	8.84
4	3.66	12.5
5	5.20	17.7
6	7.30	25.0
7	10.4	35.4
8	14.6	50.0
9	20.8	70.8
10	29.2	100.0



S_1 INPUT SELECTOR
S_2 FINE GAIN CONTROL
R_1 CENTERING CONTROL

ALL RESISTANCES IN OHMS
$1K = 10^3$ OHMS
$1M = 10^6$ OHMS
ALL RESISTORS 1/2-WATT UNLESS OTHERWISE SPECIFIED
VOLTAGES MEASURED TO GROUND

FIG. 5. MODIFIED VERTICAL AMPLIFIER: DU MONT CATHODE-RAY OSCILLOGRAPH TYPE 208.

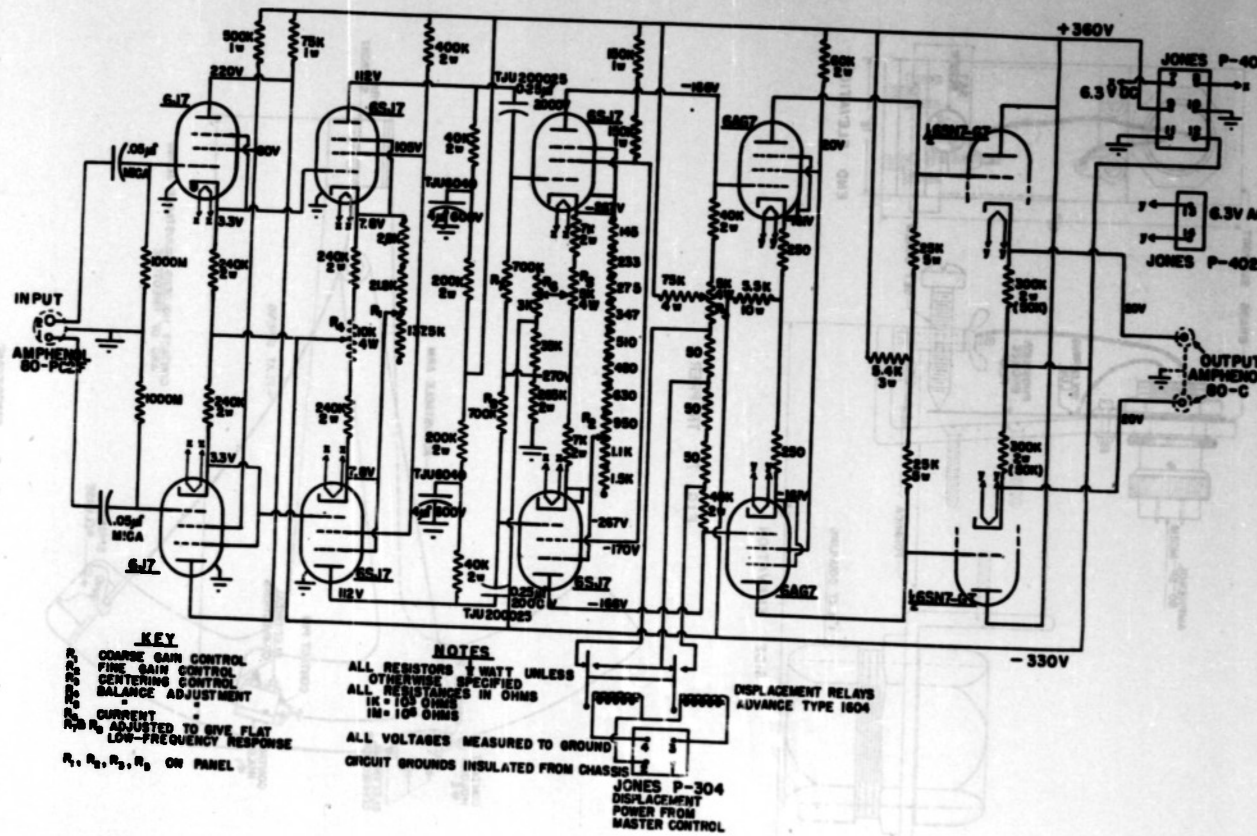


FIG. 6. AMPLIFIER FOR EIGHT-CHANNEL OSCILLOGRAPH IN MOBILE LABORATORY.

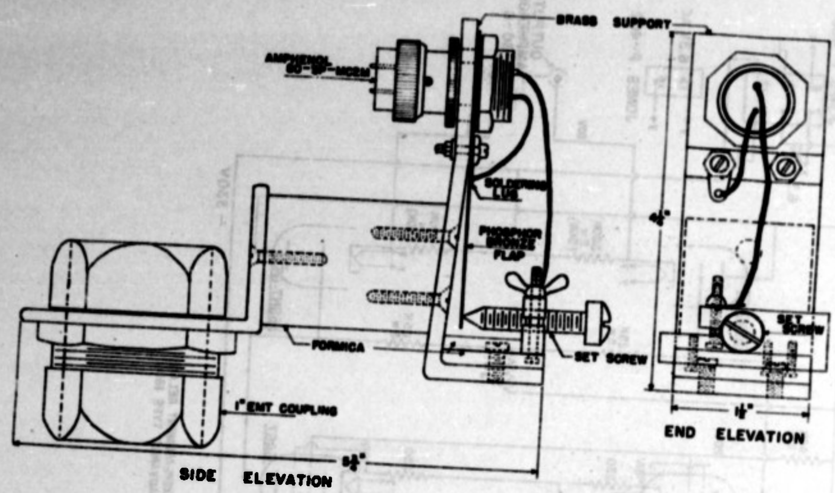


FIG. 7. TRIPPER.

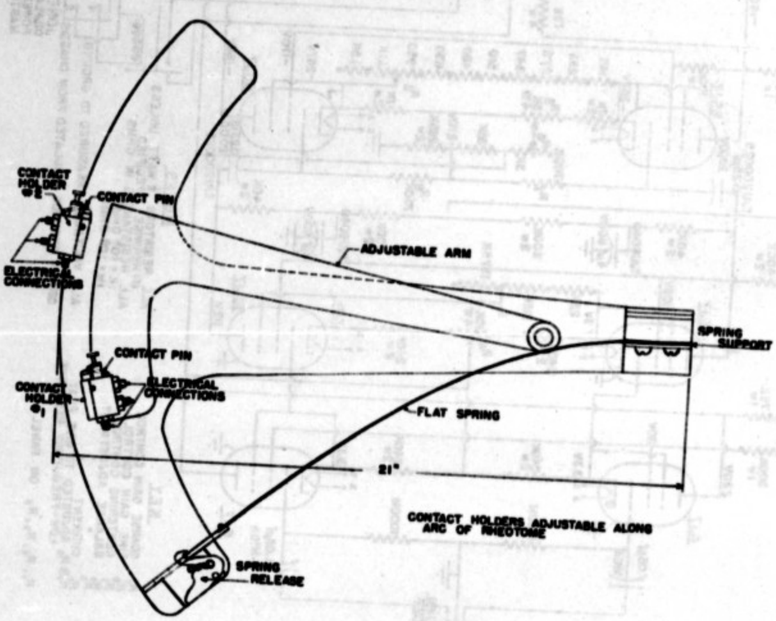


FIG. 8. RHEOTOME.

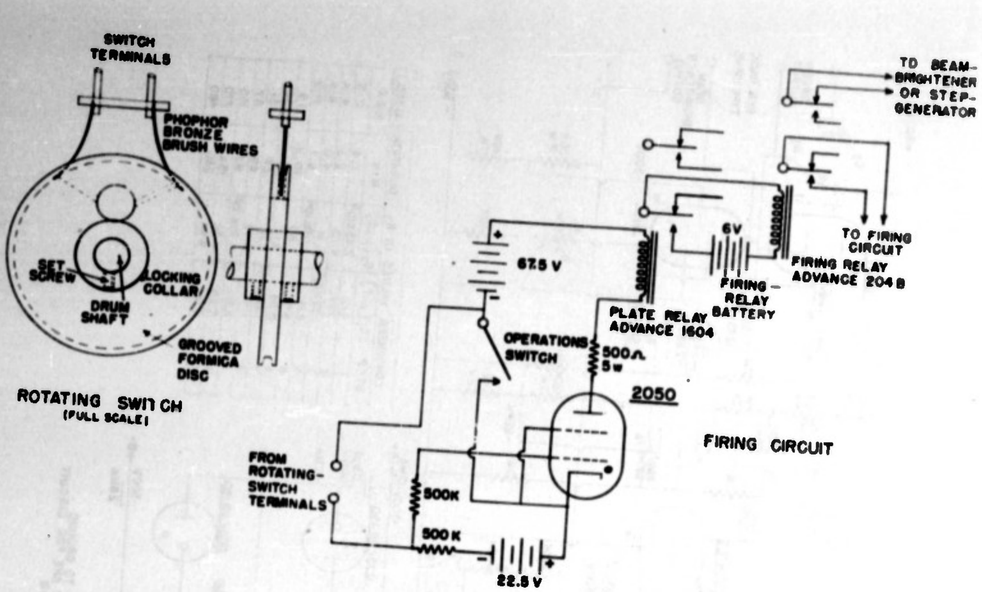


FIG. 9. DRUM-SYNCHRONIZED FIRING CIRCUIT USING ROTATING SWITCH.

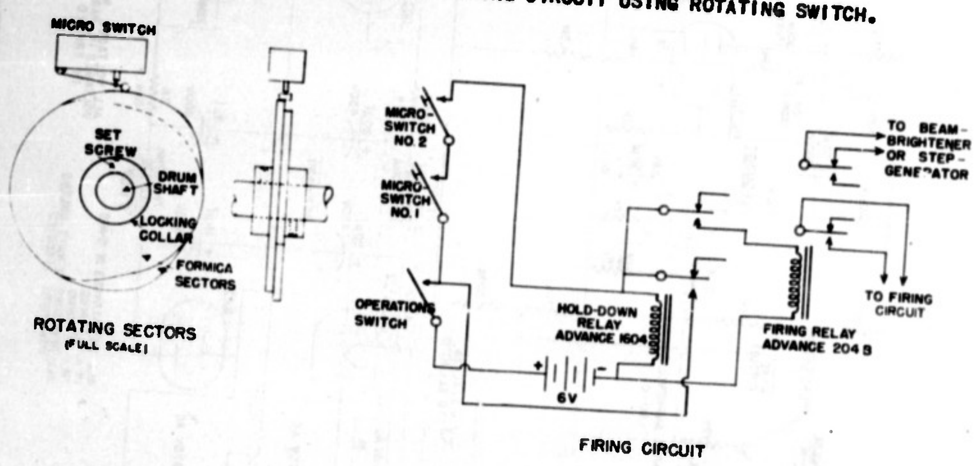
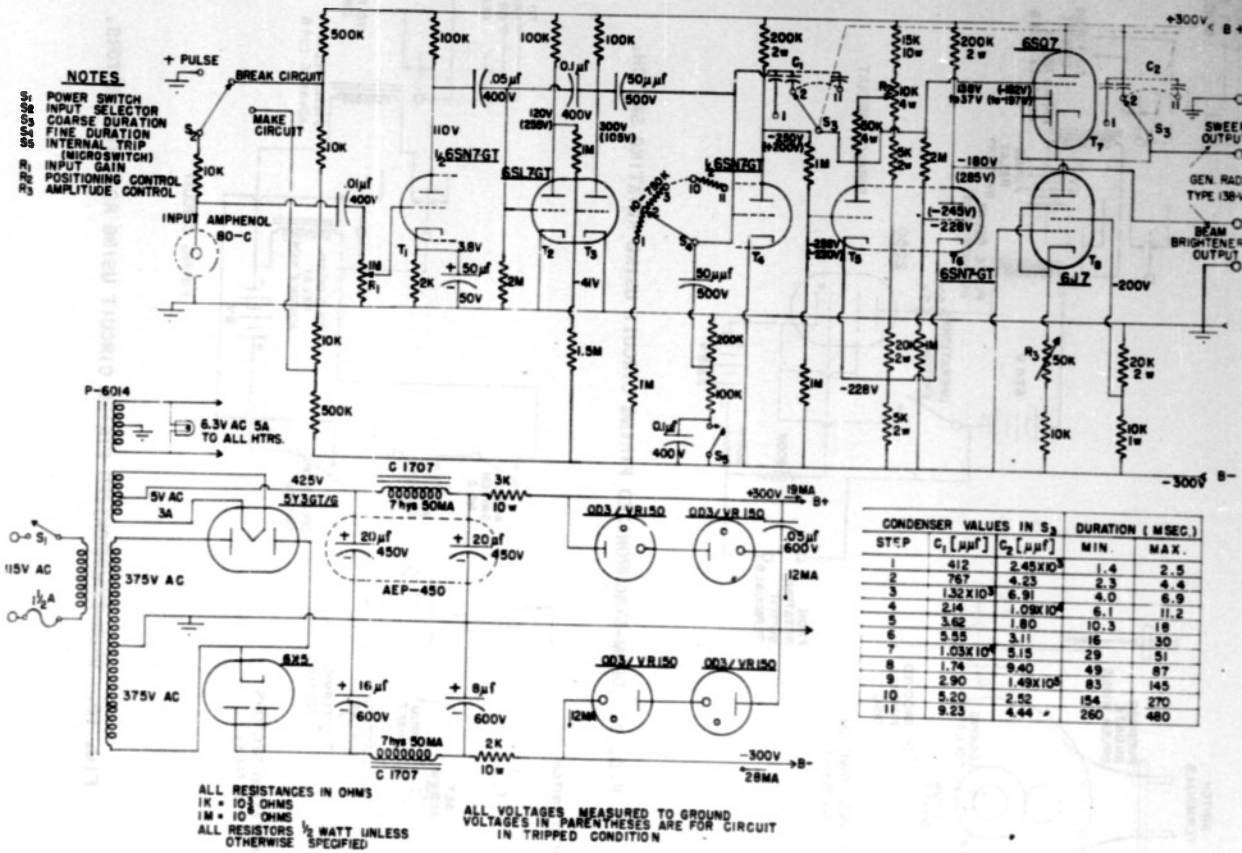
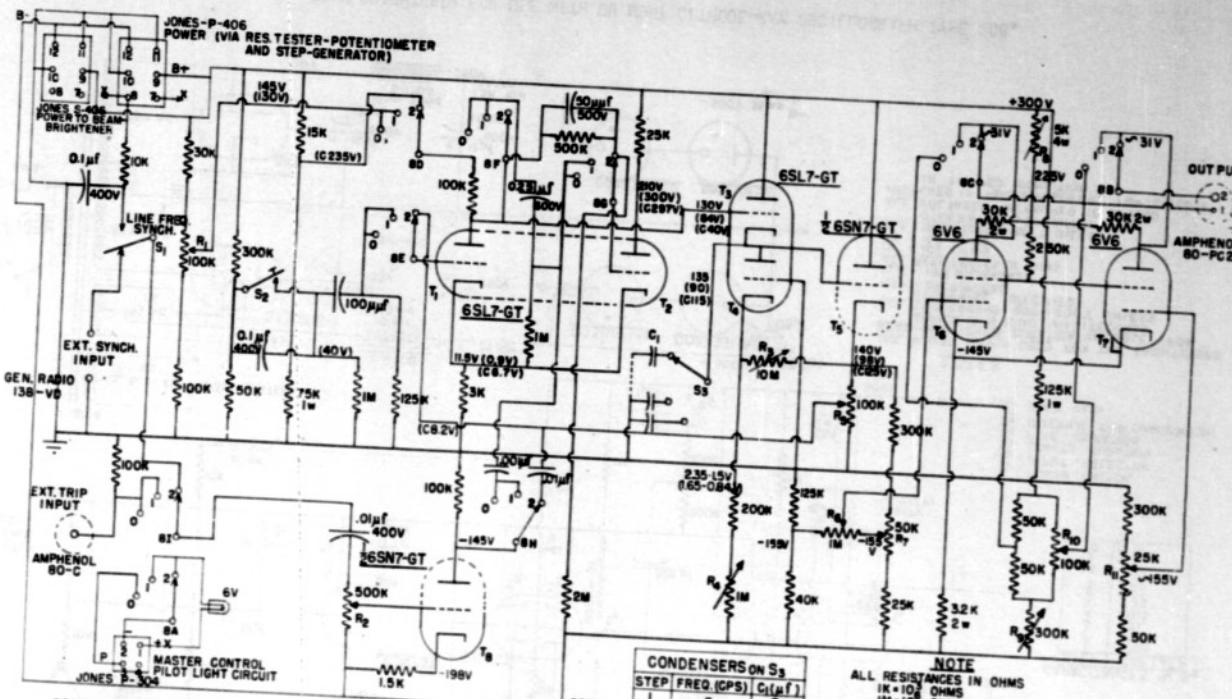


FIG. 10. DRUM-SYNCHRONIZED FIRING CIRCUIT USING ROTATING SECTORS.



CONDENSER VALUES IN S_3			DURATION (MSEC.)	
STEP	C_1 [$\mu\mu f$]	C_2 [$\mu\mu f$]	MIN.	MAX.
1	412	2.45×10^3	1.4	2.5
2	767	4.23	2.3	4.4
3	1.32×10^3	6.91	4.0	6.9
4	2.14	1.09×10^4	6.1	11.2
5	3.62	1.80	10.3	18
6	5.55	3.11	16	30
7	1.03×10^4	5.15	29	51
8	1.74	9.40	49	87
9	2.90	1.49×10^5	83	145
10	5.20	2.52	154	270
11	9.23	4.44 "	260	480

FIG. 11. SINGLE-SWEEP-GENERATOR AND BEAM-BRIGHTENER FOR USE WITH DU MONT CATHODE-RAY OSCILLOGRAPH TYPE 208.



CONTROLS ON PANEL

S_1	SYNCH. SIGNAL SELECTOR
S_2	INTERNAL TRIP (MICROSWITCH)
S_3	COARSE FREQUENCY
8A, 8B, ETC.	GANGED ROTARY SWITCHES LETTER INDICATES GANG 0-OFF, 1-SINGLE SWEEP, 2-CONTINUOUS SWEEP
R_2	SYNCH. AND TRIP GAIN
R_4	FINE FREQUENCY
R_6	AMPLITUDE
R_{11}	CENTERING

CONTROLS ON CHASSIS

R_1	ADJUSTED TO MAKE INITIAL POSITION OF SINGLE AND CONTINUOUS SWEEP COINCIDE
R_3	LINEARITY ADJUSTMENT
R_5	FEEDBACK FOR CONTINUOUS SWEEP
R_7	SET TO OBTAIN ZERO V. ACROSS R_6 FOR UNTRIPPED SINGLE SWEEP
R_8	OUTPUT MEAN POTENTIAL CONTROL SWEEP ON
R_9	" " " " OFF.
R_{10}	CENTERING, SWEEP OFF.

NOTE

ALL VOLTAGES MEASURED TO GROUND
( ) INDICATES CIRCUIT TRIPPED, SINGLE SWEEP
(C) INDICATES CIRCUIT ON CONTINUOUS SWEEP

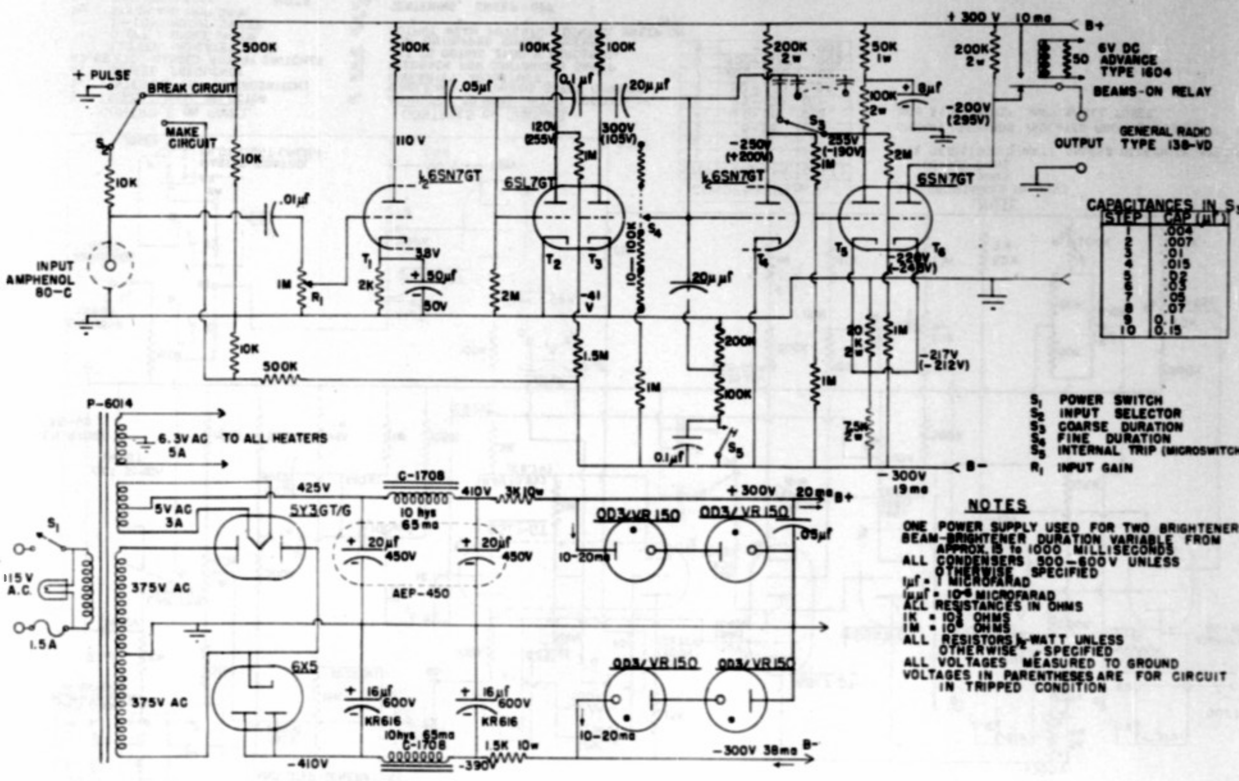
CONDENSERS ON S_3		
STEP	FREQ. (CPS)	C_1 (μf)
1	-	2
2	3-10	1
3	5-25	0.5
4	12.5-50	0.2
5	25-100	0.1
6	50-250	.05
7	200-500	.02
8	500-1677	.005
9	-	.002

NOTE

ALL RESISTANCES IN OHMS
$1K = 10^3$ OHMS
$1M = 10^6$ OHMS
ALL RESISTORS ½-WATT UNLESS OTHERWISE SPECIFIED

CIRCUIT GROUNDS ISOLATED FROM CHASSIS
XX 6.3 VAC HEATER SUPPLY, ALL TUBES

FIG. 12. CONTINUOUS AND SINGLE SWEEP-GENERATOR FOR USE IN EIGHT-CHANNEL MOBILE LABORATORY.



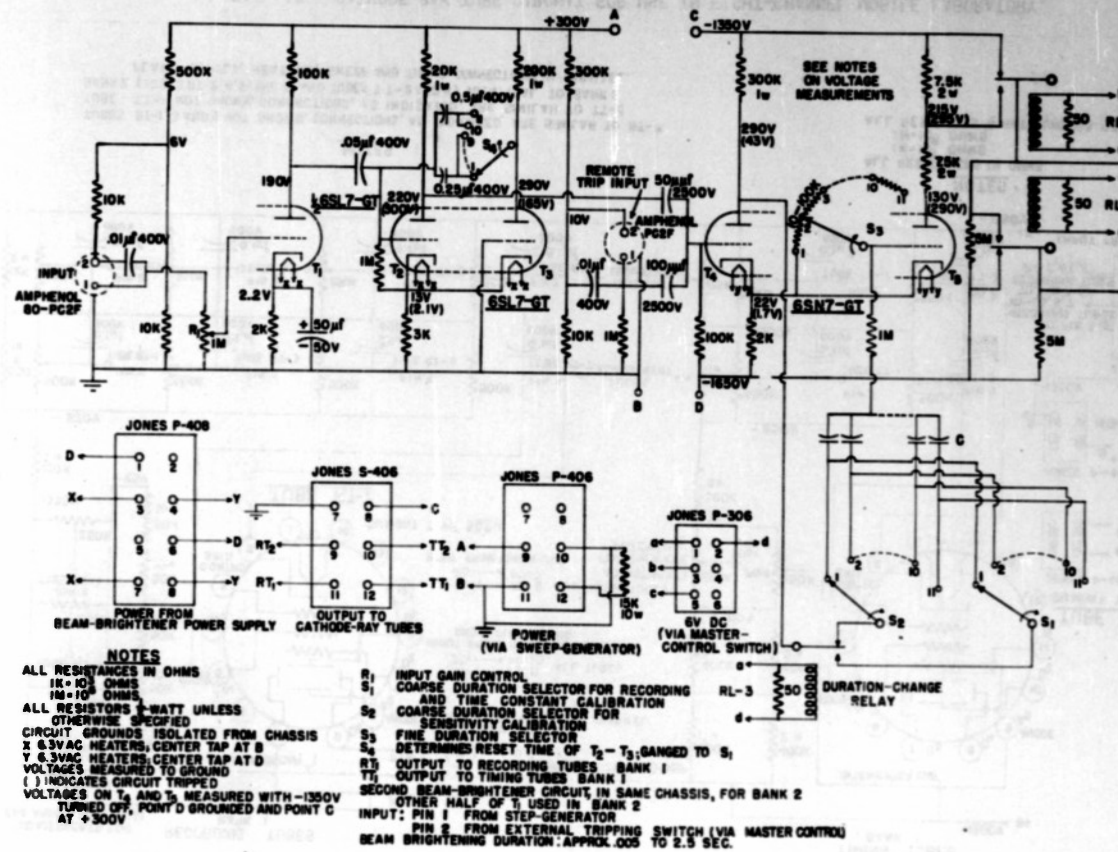
CAPACITANCES IN S_3	
STEP	CAP (μf)
1	.004
2	.007
3	.01
4	.015
5	.02
6	.03
7	.05
8	.07
9	0.1
10	0.15

S_1 POWER SWITCH
S_2 INPUT SELECTOR
S_3 COARSE DURATION
S_4 FINE DURATION
S_5 INTERNAL TRIP (MICROSWITCH)
R_1 INPUT GAIN

NOTES

ONE POWER SUPPLY USED FOR TWO BRIGHTENERS
BEAM-BRIGHTENER DURATION VARIABLE FROM APPROX. 15 to 1000 MILLISECONDS
ALL CONDENSERS 300–600V UNLESS OTHERWISE SPECIFIED
1μf = 1 MICROFARAD
1μμf = 10^{-6} MICROFARAD
ALL RESISTANCES IN OHMS
1K = 10^3 OHMS
1M = 10^6 OHMS
ALL RESISTORS ½-WATT UNLESS OTHERWISE SPECIFIED
ALL VOLTAGES MEASURED TO GROUND
VOLTAGES IN PARENTHESES ARE FOR CIRCUIT IN TRIPPED CONDITION

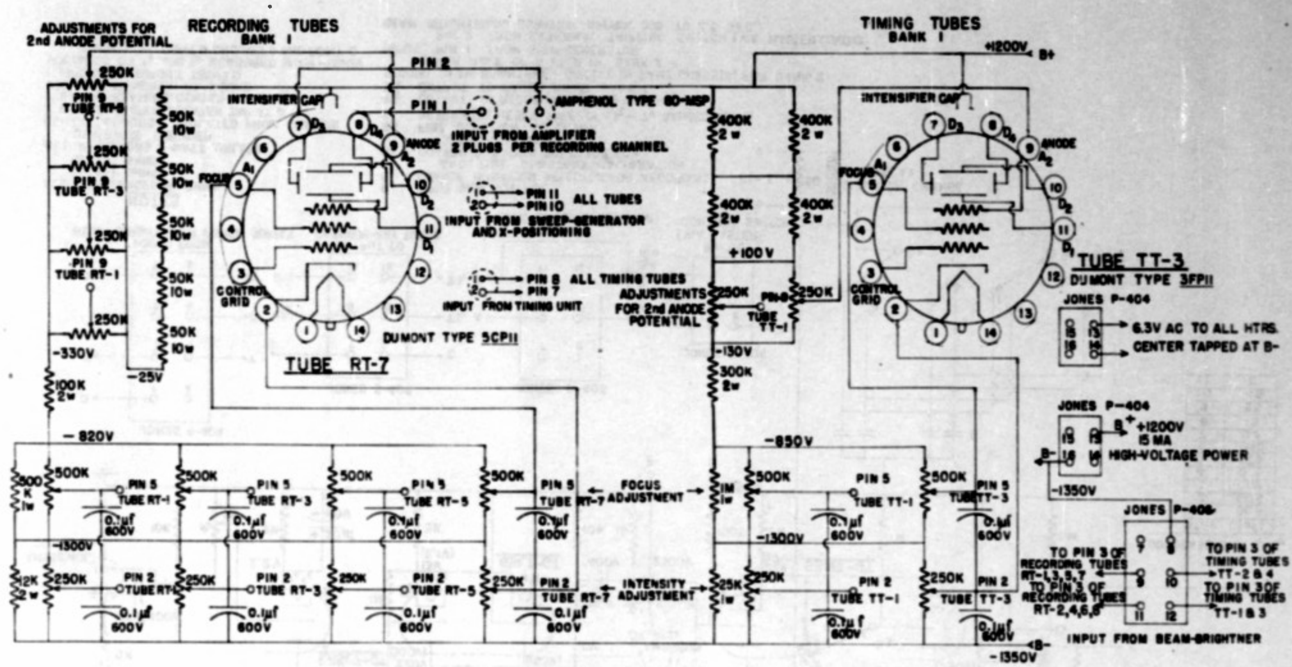
FIG. 13. BEAM-BRIGHTENER FOR USE WITH DU MONT CATHODE-RAY OSCILLOGRAPH TYPE 208.



CONDENSERS IN $S_1 - S_3$

STEP	C(μf)
1	.003
2	.005
3	.009
4	.015
5	.025
6	.035
7	.08
8	.15
9	.25
10	.45
11	.8

FIG. 14. BEAM-BRIGHTENER FOR USE IN EIGHT-CHANNEL MOBILE LABORATORY.



NOTES

TUBES RT-1,3 AND 5 NOT SHOWN. CONNECTIONS, AS INDICATED, ARE SIMILAR TO RT-7
TUBE TT-1 NOT SHOWN. CONNECTIONS, AS INDICATED, ARE SIMILAR TO TT-3
BANK 2 (TUBES RT-2,4,6, AND 8, AND TUBES TT-2 AND 4) IDENTICAL TO BANK I.
PLATE SUPPLY, HEATERS, SWEEP AND TIMING CONNECTIONS IN PARALLEL.

NOTES

ALL RESISTANCES IN OHMS
$1K = 10^3$ OHMS
$1M = 10^6$ OHMS
ALL RESISTORS ½ WATT UNLESS OTHERWISE SPECIFIED

FIG. 15. CATHODE-RAY TUBE CIRCUIT FOR USE IN EIGHT-CHANNEL MOBILE LABORATORY.

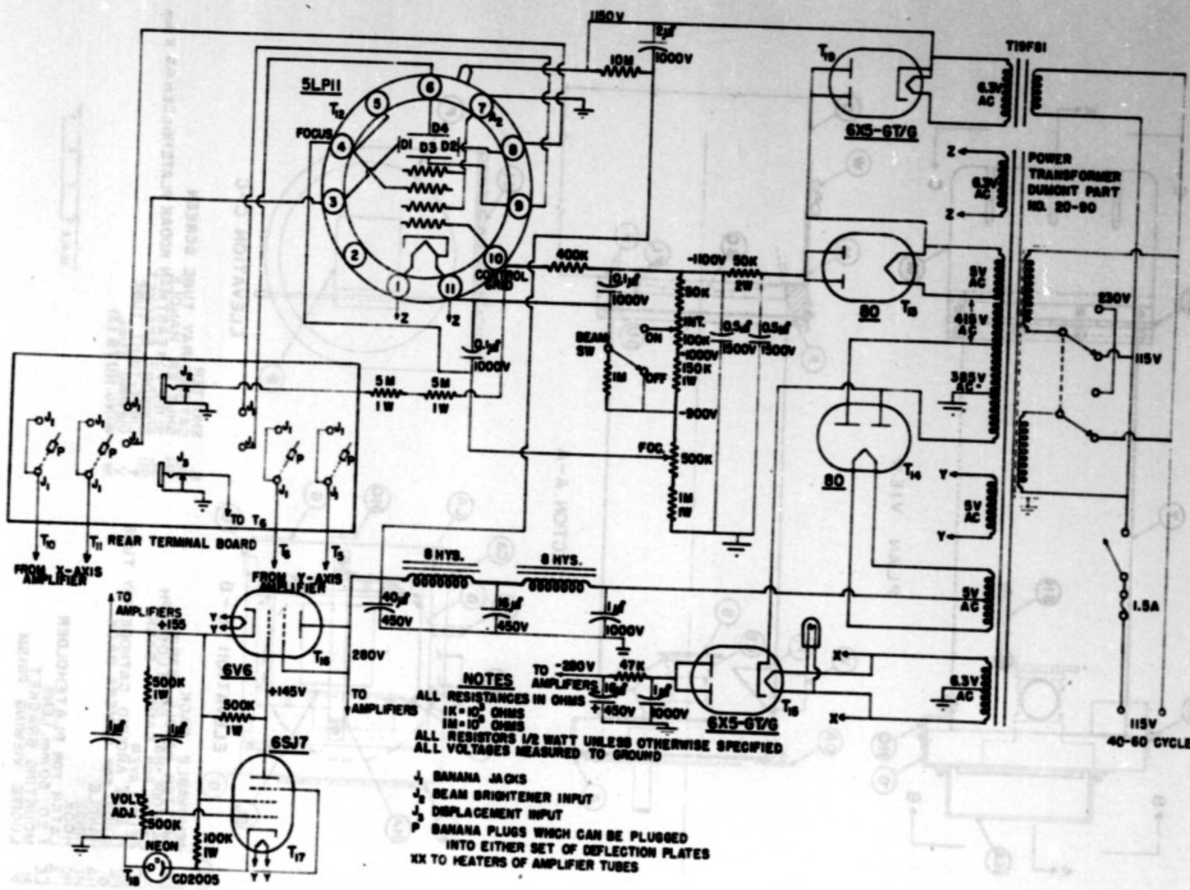
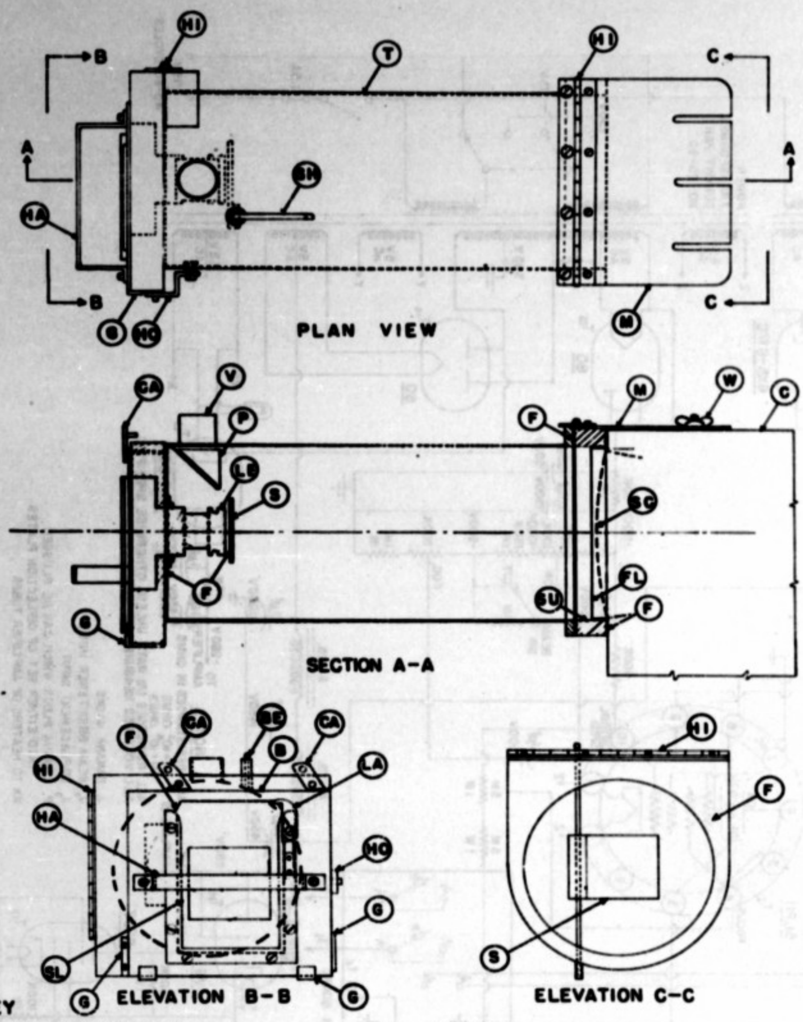


FIG. 16. MODIFIED POWER SUPPLY AND CATHODE-RAY TUBE CIRCUIT: DU MONT CATHODE-RAY OSCILLOGRAPH TYPE 208.



KEY

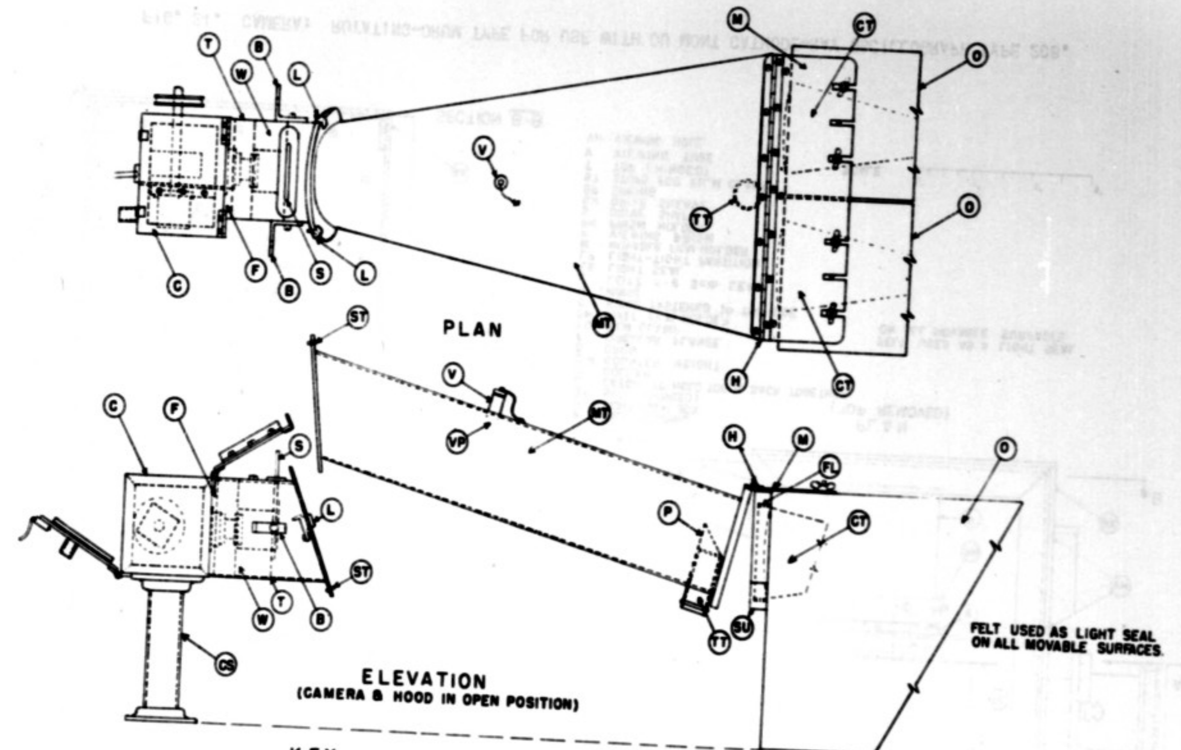
B	REMOVABLE BACK	S	SHUTTER
BE	SHUTTER HANDLE BEARING	SC	CATHODE-RAY TUBE SCREEN
C	CATHODE-RAY OSCILLOGRAPH	SH	SHUTTER HANDLE
CA	CATCH FOR CAMERA BACK	SL	SLIDE FOR EASTMAN KODAK PLATEHOLDER 6.5 X 9cm
F	FELT LAYER	SU	SUPPORT BRACKET
FL	FLANGE AROUND CATHODE-RAY TUBE	T	LIGHT-TIGHT TUBE
G	GUIDE FOR CAMERA BACK	V	VIEWING TUBE
HA	HANDLE	W	WING NUTS (3)
HI	HINGE		
HO	HOOK		
LA	LATCH FOR PLATEHOLDER		
LE	f 2.0 50 mm. LENS		
M	MOUNTING BRACKET		
P	LUCITE VIEWING PRISM		

SCALE 0 1 2 3

FIG. 17. CAMERA: CUT-FILM TYPE FOR USE WITH DU MONT CATHODE-RAY OSCILLOGRAPH TYPE 208.

FIGURE 18. CATHODE-RAY TUBES, CAMERA LENSES, AND CAMERA MIRROR IN MOBILE LABORATORY

FIGURE 19. INTERIOR OF DRUM CAMERA IN MOBILE LABORATORY



KEY

B BRACKET FOR MOUNTING IN DARKROOM WALL
C CAMERA
CS CAMERA SUPPORT FOR TABLE USE
CT CATHODE-RAY TUBE
F CIRCULAR FLANGE
FL FLANGE AROUND CATHODE-RAY TUBE
H HINGE
L LATCH FOR HOLDING TWO LIGHT-TIGHT TUBES TOGETHER
M MOUNTING BRACKET
MT MOVABLE LIGHT-TIGHT TUBE
O CATHODE-RAY OSCILLOGRAPH
P PRISM FOR TIMING TUBE
S SHUTTER
ST STOP
SU SUPPORT BRACKET
T LIGHT-TIGHT TUBE
TT HOLDER FOR TIMING TUBE
V VIEWING TUBE AND CAP
VP VIEWING PRISM
W WOODEN SUPPORT FOR SHUTTER

SCALE

FIG. 20. CAMERA: ROTATING-DRUM TYPE FOR USE WITH DU MONT CATHODE-RAY OSCILLOGRAPH TYPE 208 TWO-CHANNEL ASSEMBLY WITH TIMING UNIT.

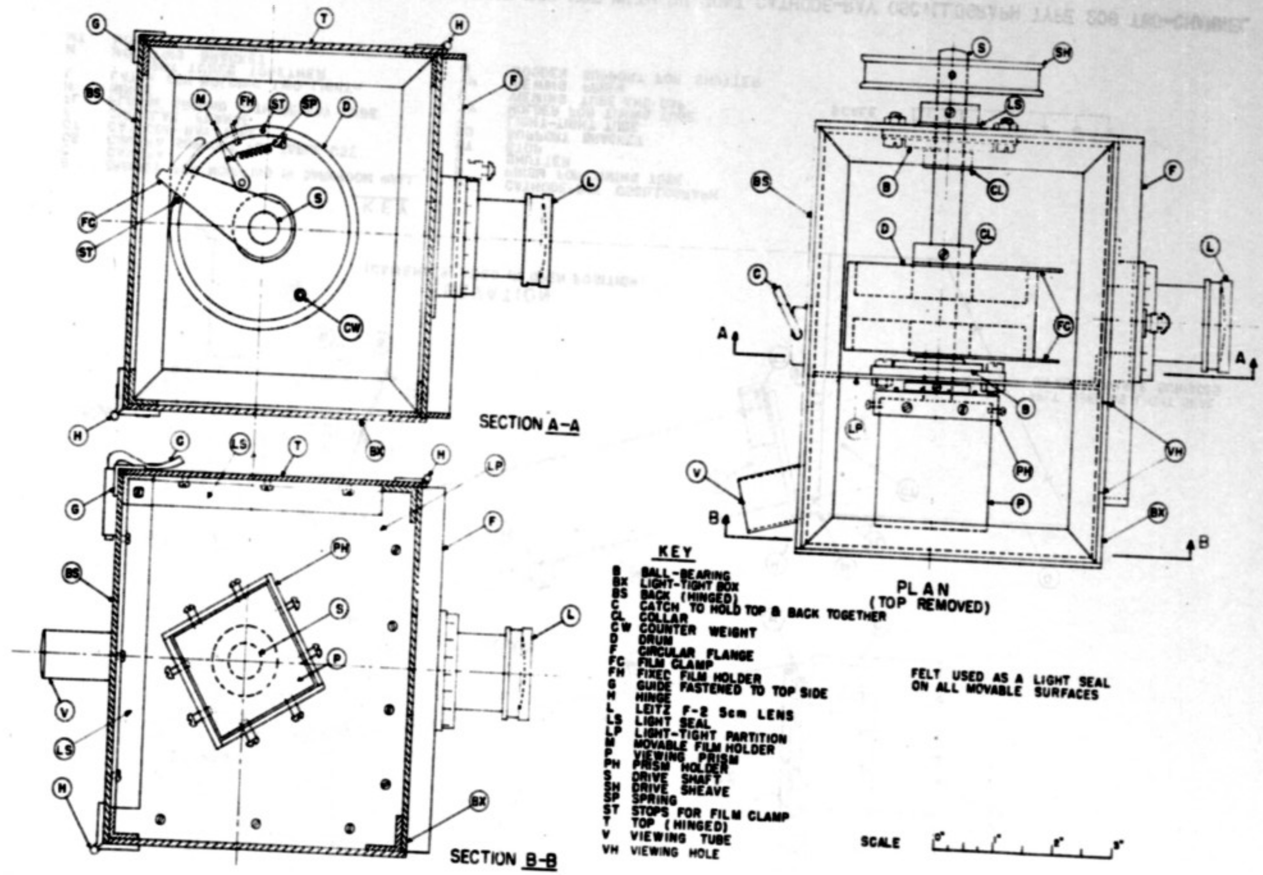


FIG. 21. CAMERA: ROTATING-DRUM TYPE FOR USE WITH DU MONT CATHODE-RAY OSCILLOGRAPH TYPE 208.

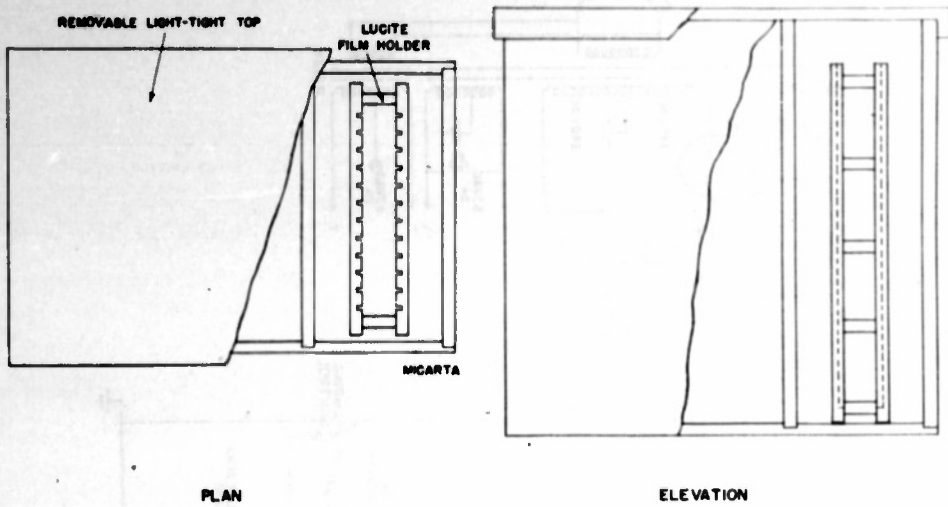


FIG. 22. DEVELOPING TANK.

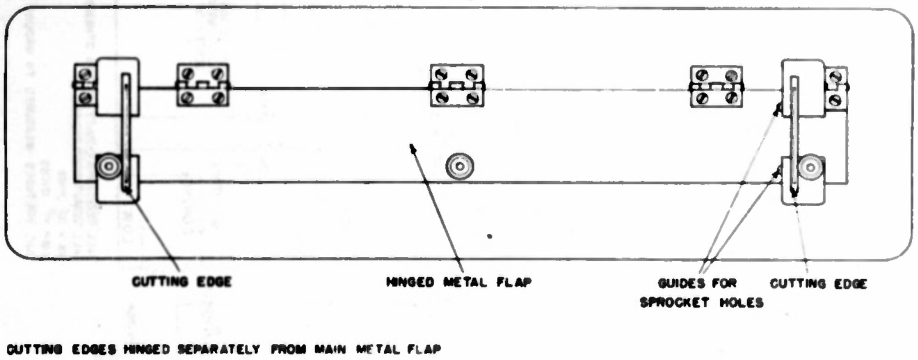


FIG. 23. FILM CUTTER.

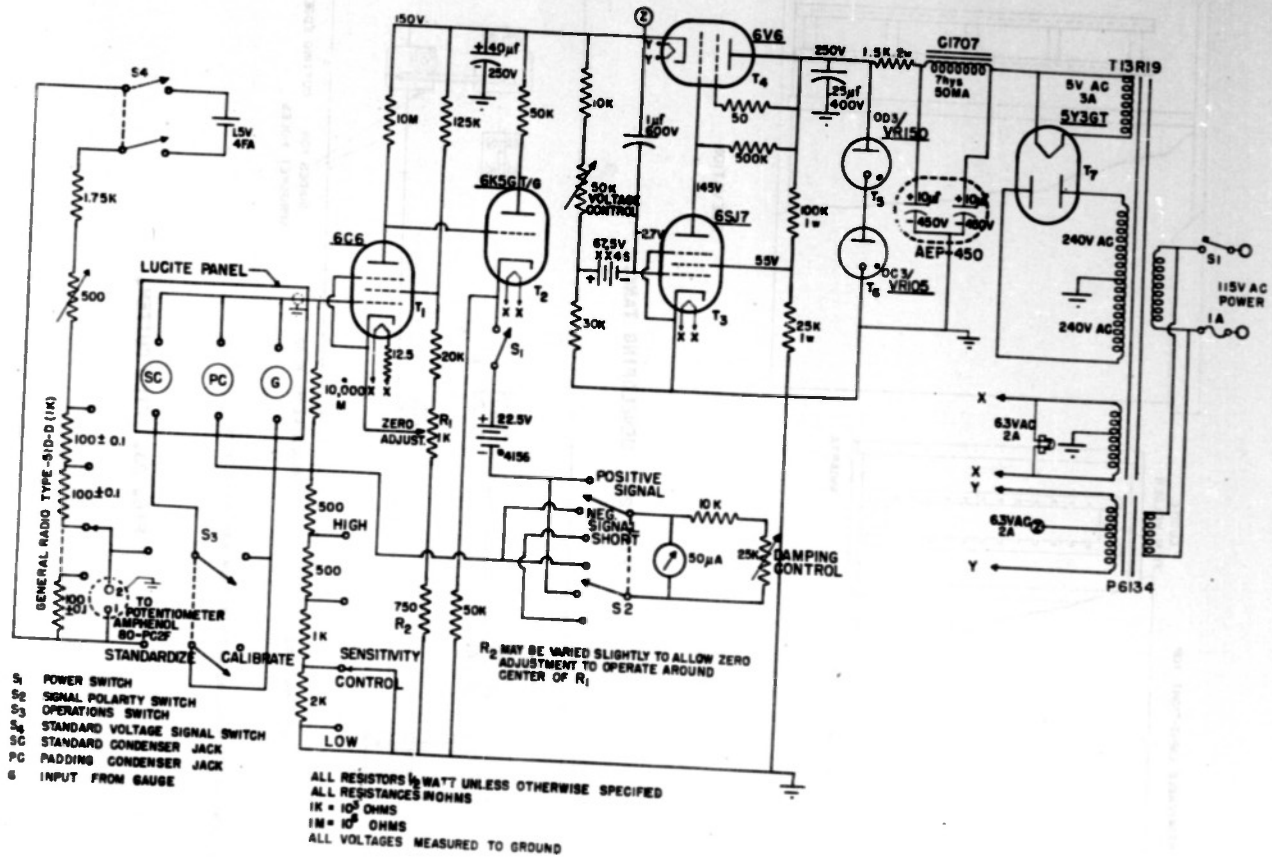
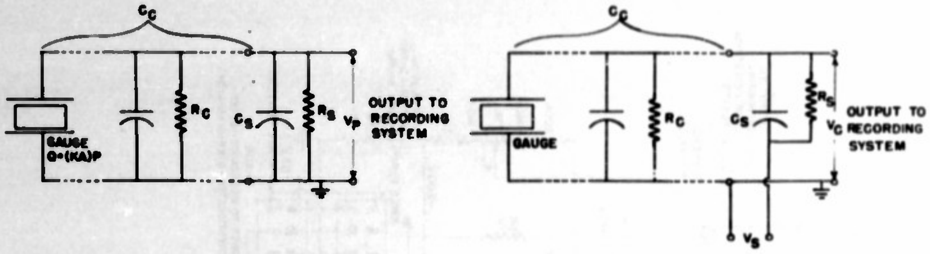


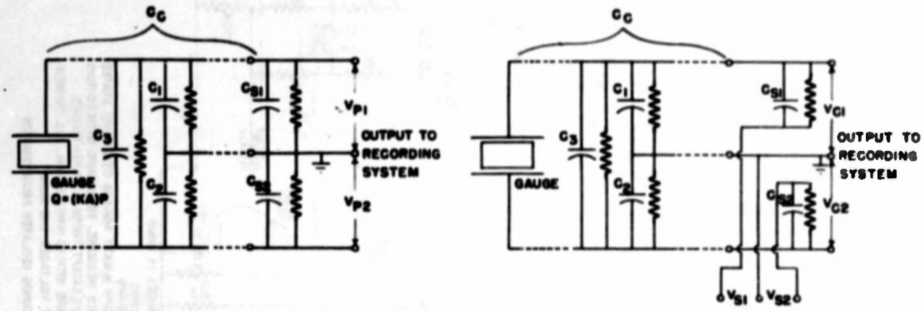
FIG. 24. MICROCOULOMETER TYPE 2.



a. CONNECTION FOR PRESSURE MEASUREMENT

b. CONNECTION FOR CALIBRATION

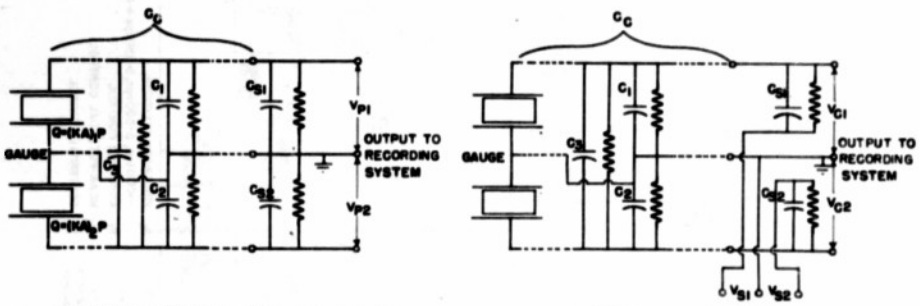
FIG. 25. UNBALANCED CABLE.



a. CONNECTION FOR PRESSURE MEASUREMENT

b. CONNECTION FOR CALIBRATION

FIG. 26. BALANCED CABLE: TYPE 1 PUSH-PULL GAUGE.



a. CONNECTION FOR PRESSURE MEASUREMENT

b. CONNECTION FOR CALIBRATION

FIG. 27. BALANCED CABLE: TYPE 2 PUSH-PULL GAUGE.

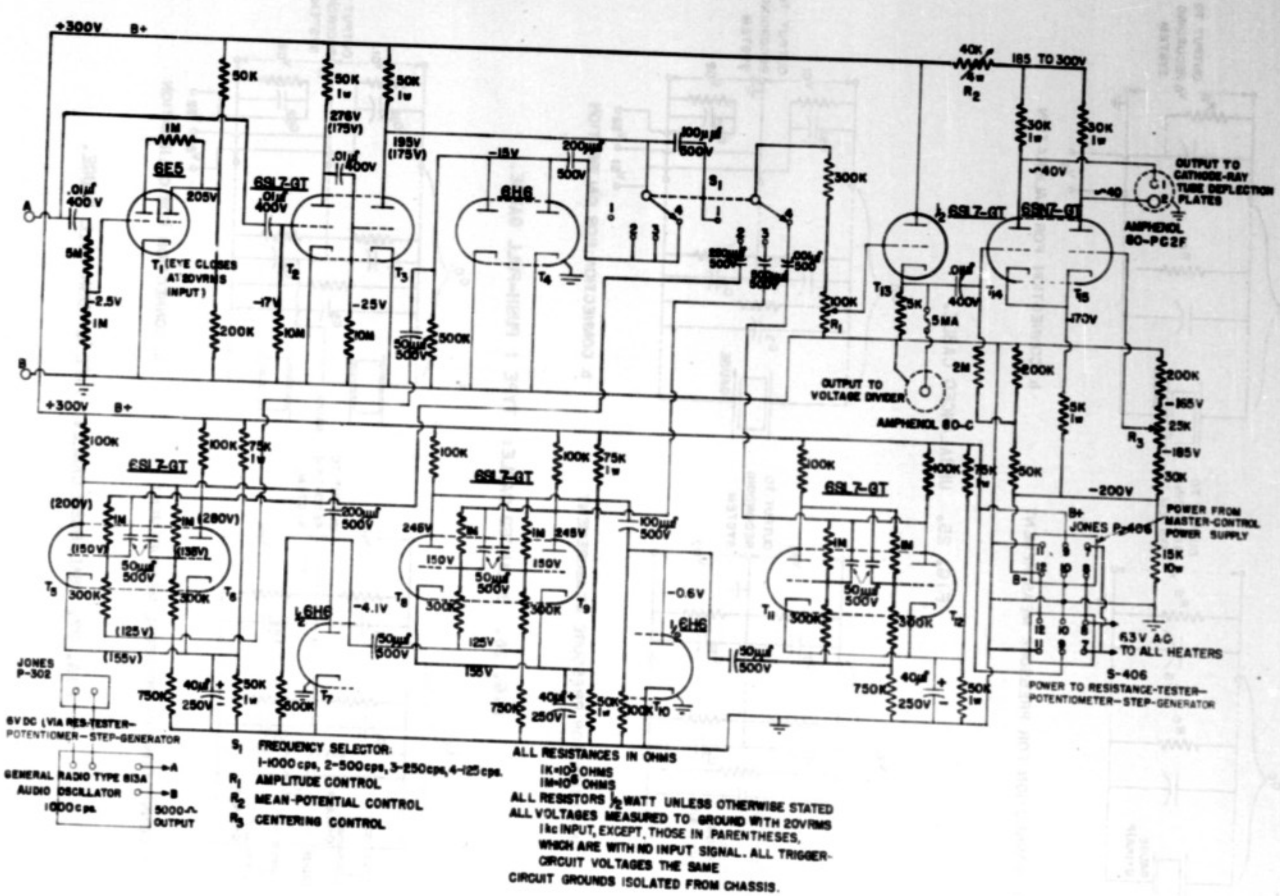
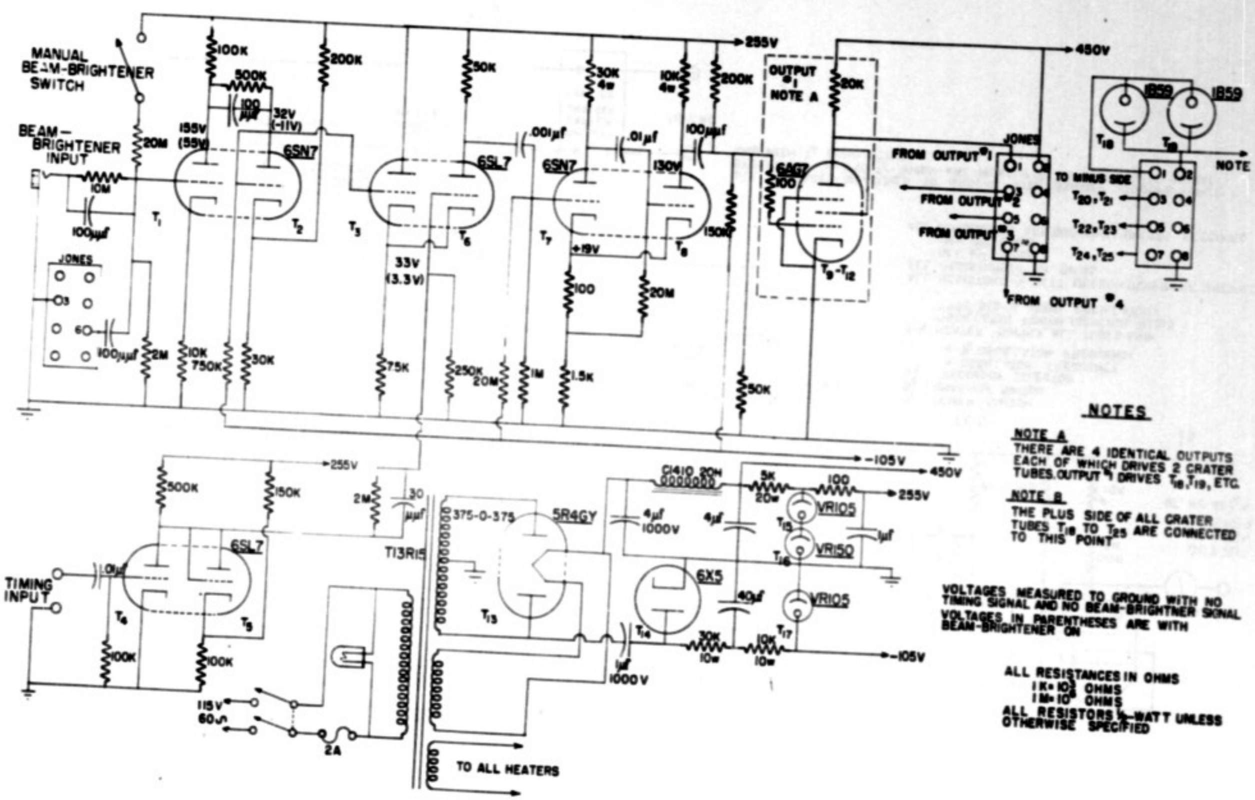


FIG. 28. TIMING UNIT FOR USE WITH EIGHT-CHANNEL MOBILE LABORATORY AND WITH DU MONT CATHODE-RAY OSCILLOGRAPH TYPE 208.



NOTES

NOTE A
THERE ARE 4 IDENTICAL OUTPUTS EACH OF WHICH DRIVES 2 CRATER TUBES. OUTPUT #1 DRIVES T_{18}, T_{19}, ETC.

NOTE B
THE PLUS SIDE OF ALL CRATER TUBES T_{18} TO T_{25} ARE CONNECTED TO THIS POINT

VOLTAGES MEASURED TO GROUND WITH NO TIMING SIGNAL AND NO BEAM-BRIGHTNER SIGNAL
VOLTAGES IN PARENTHESES ARE WITH BEAM-BRIGHTENER ON

ALL RESISTANCES IN OHMS
$1K = 10^3$ OHMS
$1M = 10^6$ OHMS
ALL RESISTORS ½-WATT UNLESS OTHERWISE SPECIFIED

FIG. 29. CRATER-TUBE TIMING CONTROL.

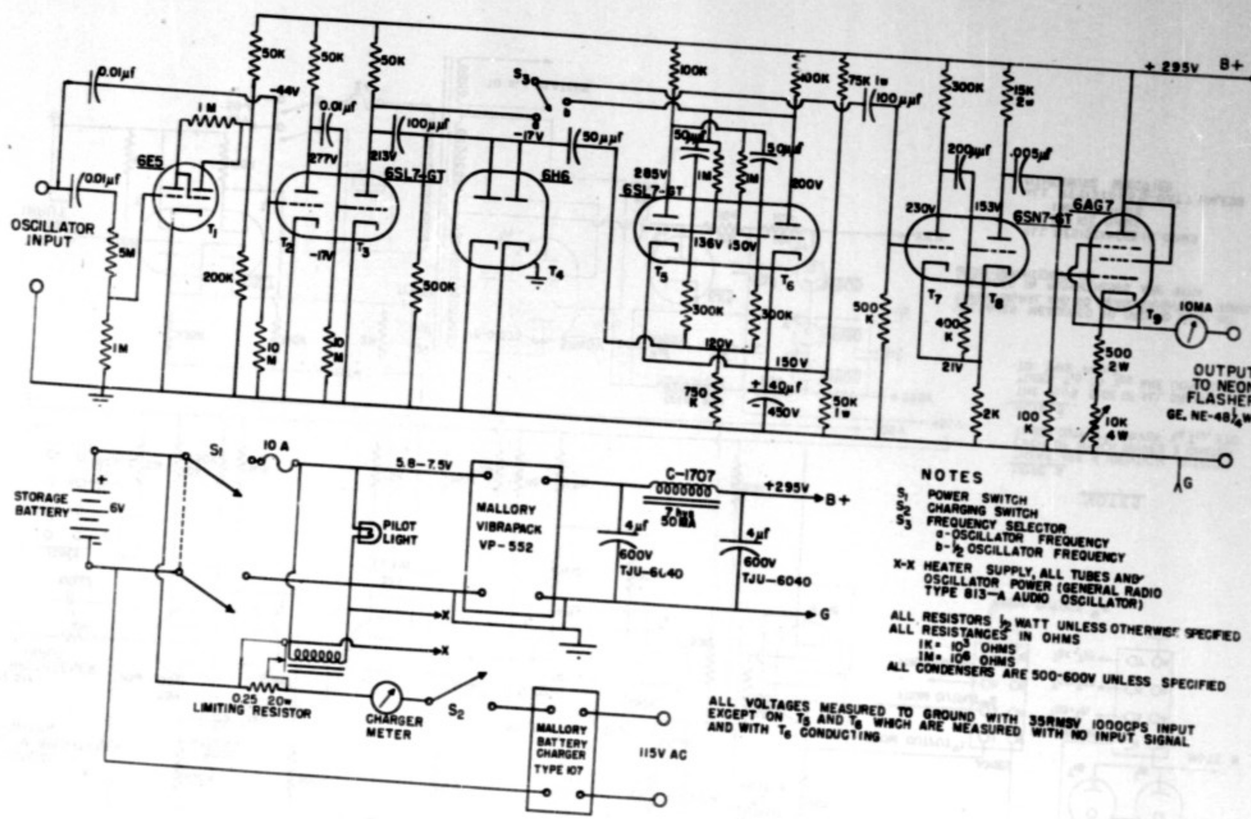


FIG. 30. TIMER FOR HIGH-SPEED CAMERA.

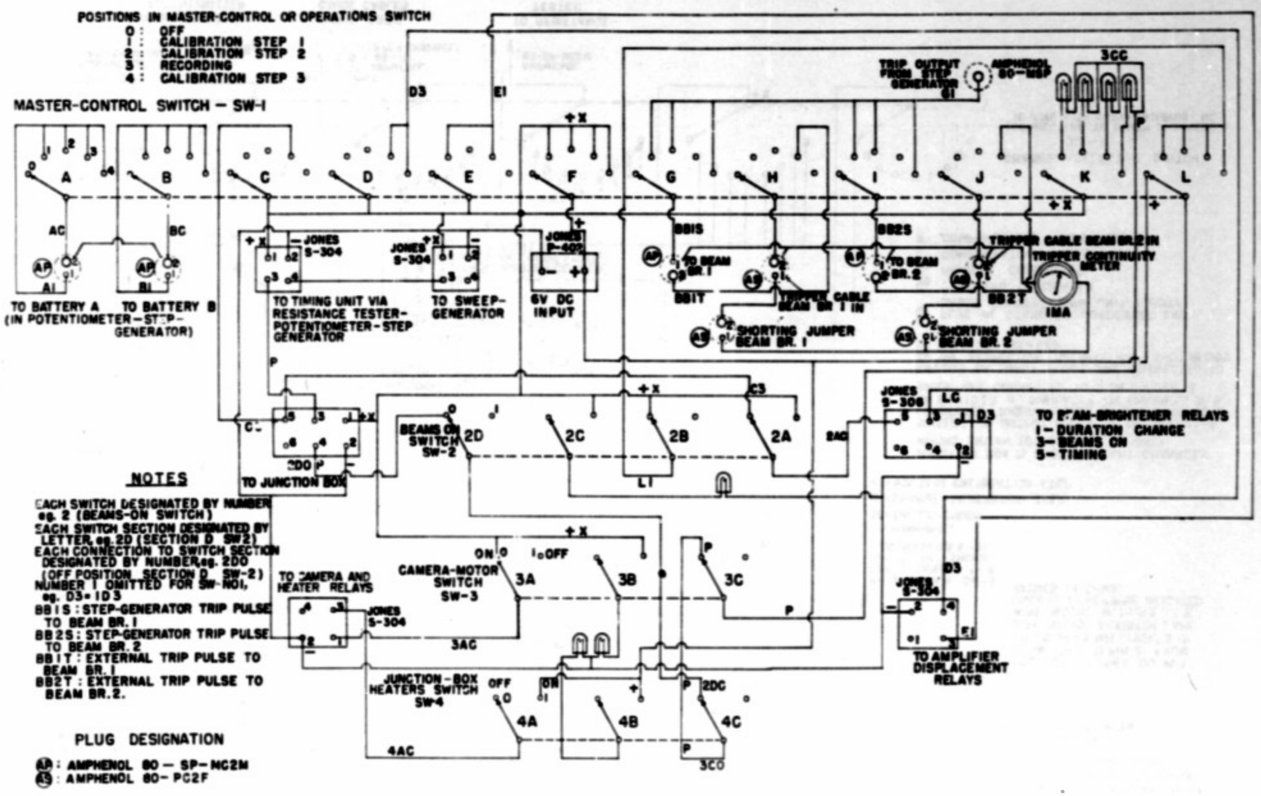


FIG. 31. MASTER CONTROL FOR USE IN EIGHT-CHANNEL MOBILE LABORATORY.

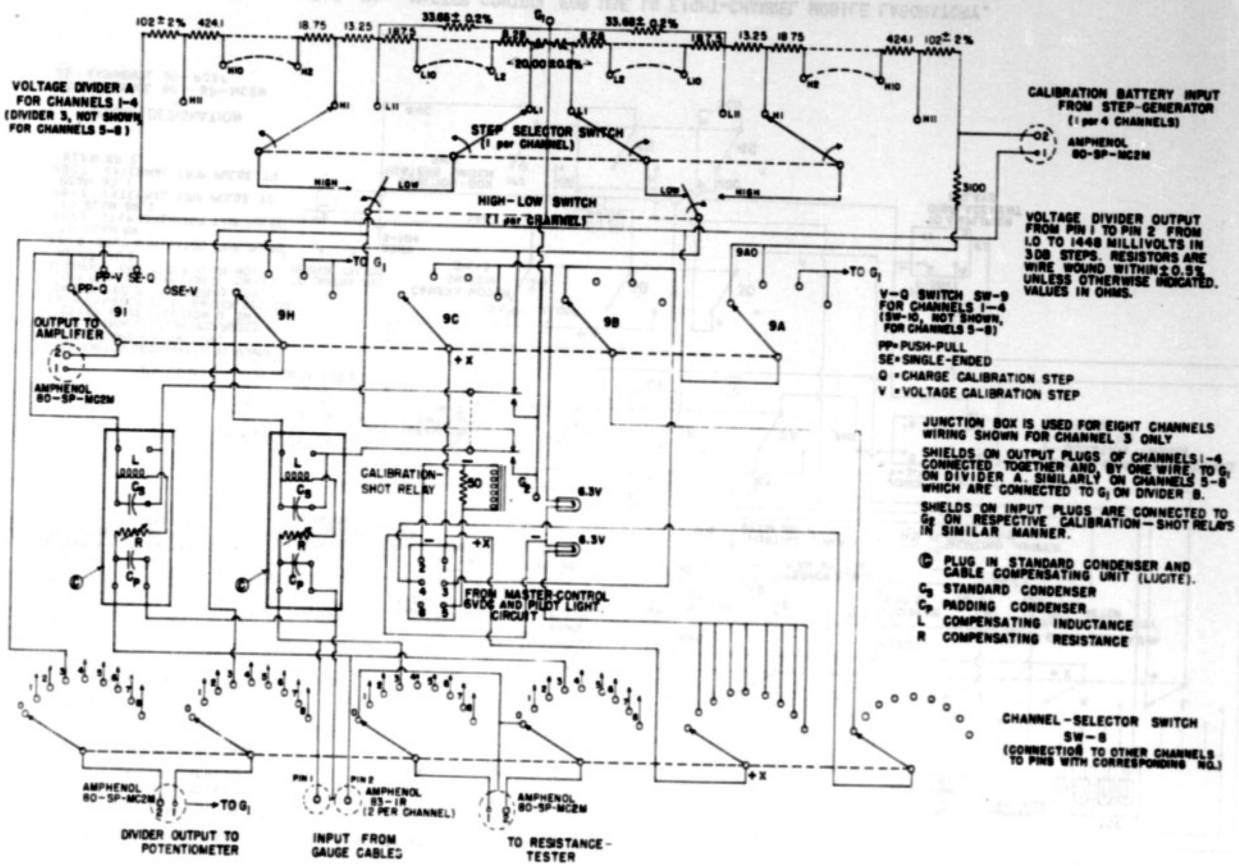


FIG. 32. JUNCTION BOX FOR USE IN EIGHT-CHANNEL MOBILE LABORATORY.

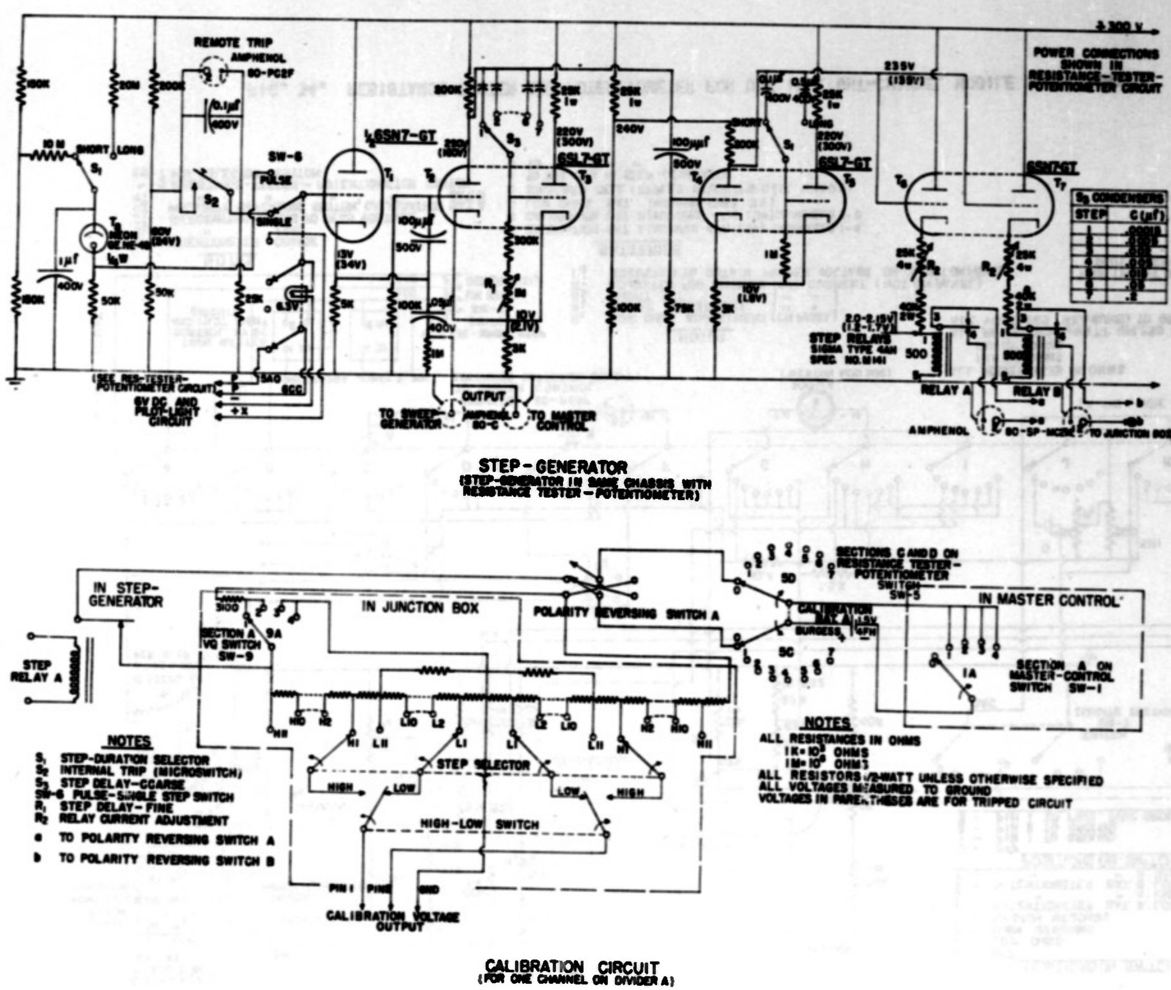


FIG. 33. STEP-GENERATOR AND CALIBRATION CIRCUIT FOR USE IN EIGHT-CHANNEL MOBILE LABORATORY.

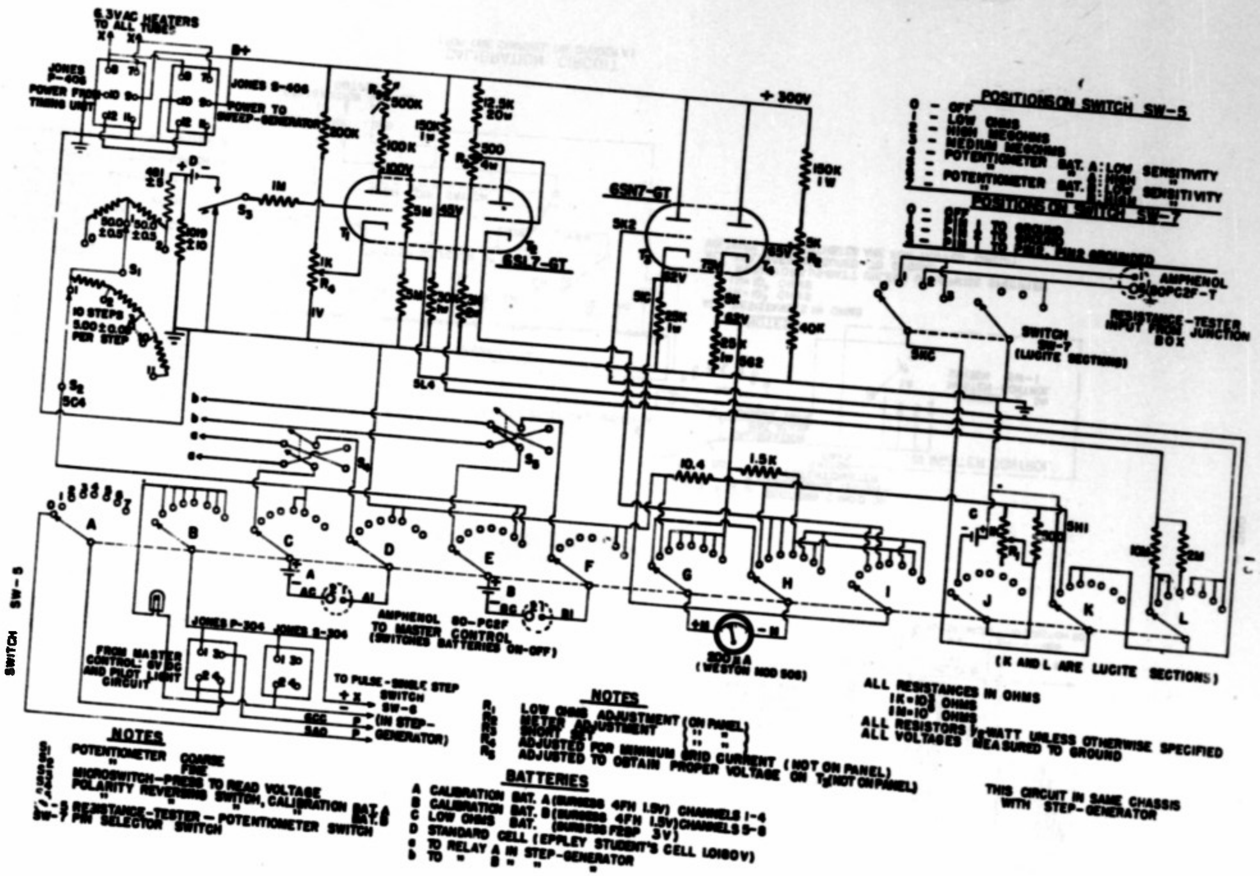


FIG. 34. RESISTANCE-TESTER AND POTENTIOMETER FOR USE IN EIGHT-CHANNEL MOBILE LABORATORY.

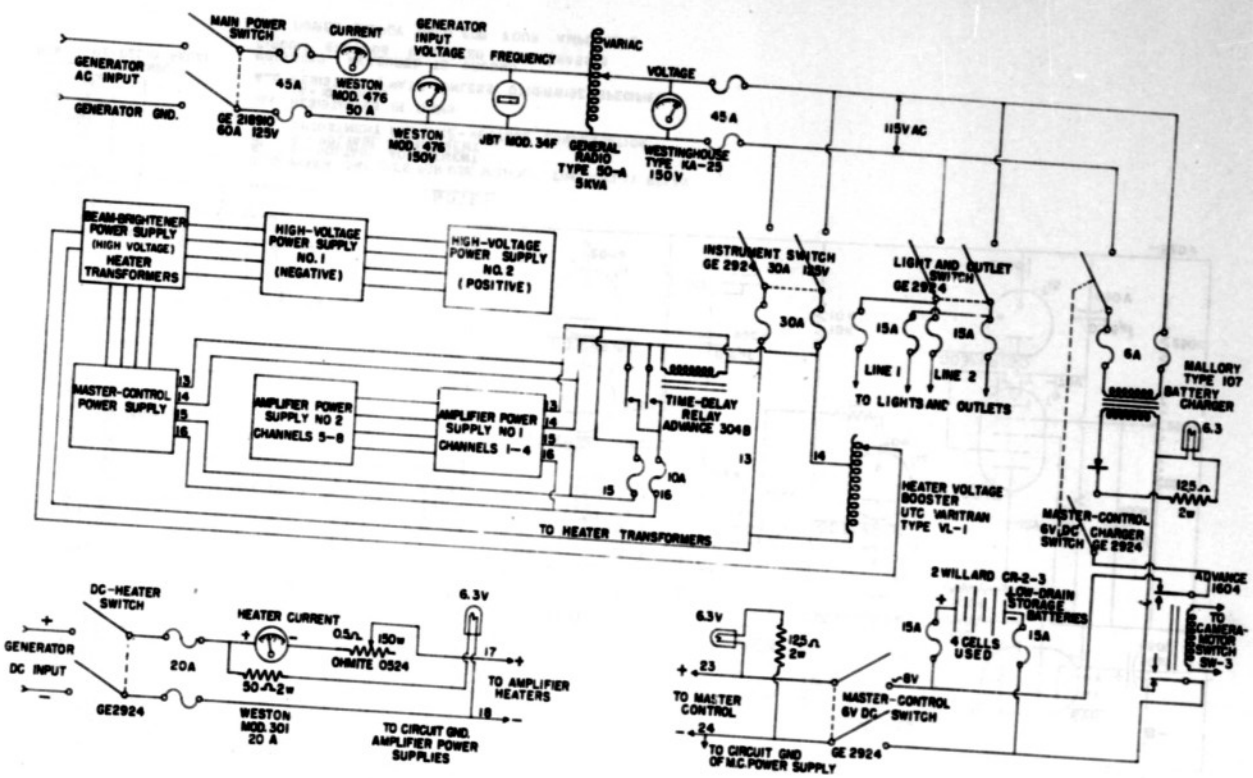
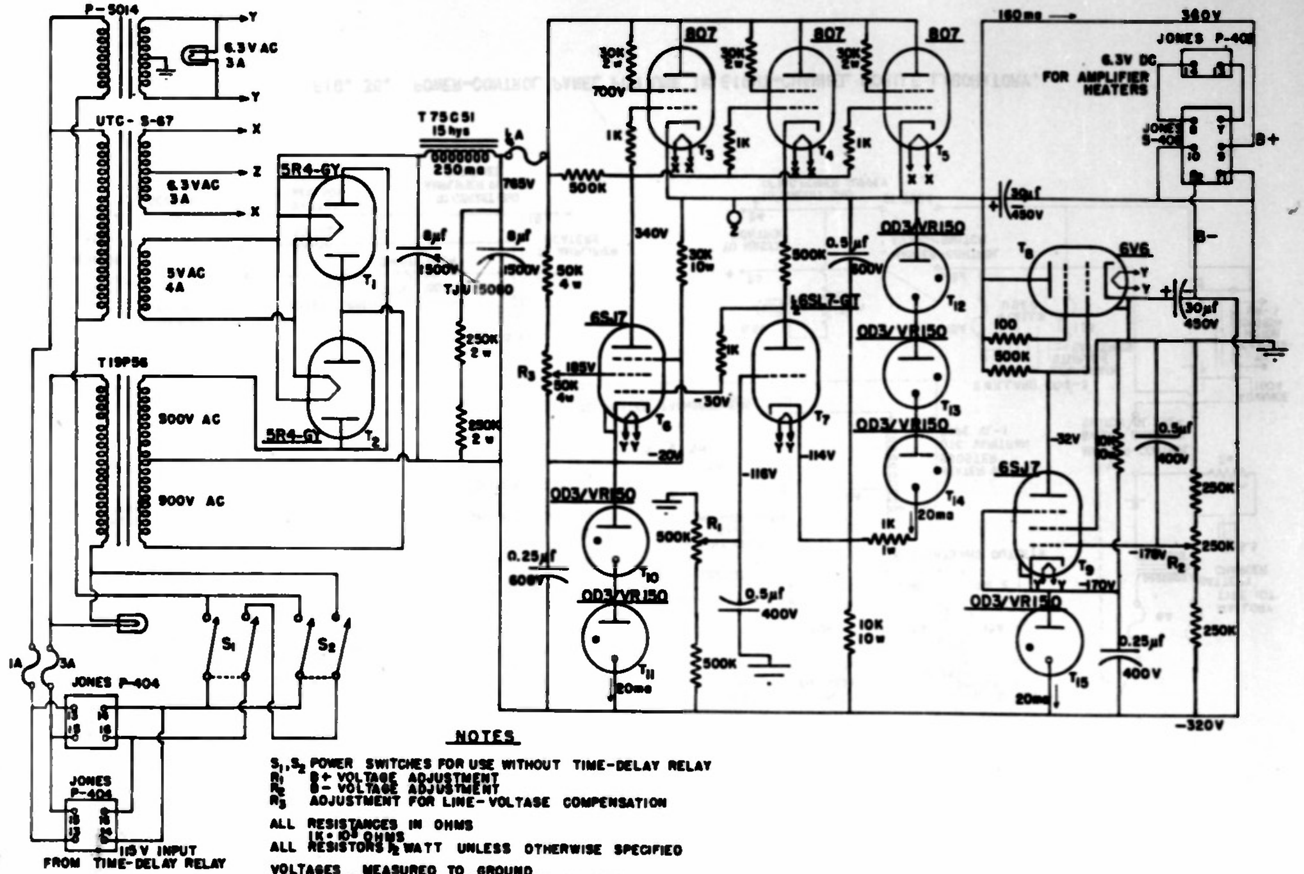


FIG. 35. POWER-CONTROL PANEL FOR USE IN EIGHT-CHANNEL MOBILE LABORATORY.



NOTES

S_1, S_2 POWER SWITCHES FOR USE WITHOUT TIME-DELAY RELAY
R_1 B+ VOLTAGE ADJUSTMENT
R_2 B- VOLTAGE ADJUSTMENT
R_3 ADJUSTMENT FOR LINE-VOLTAGE COMPENSATION

ALL RESISTANCES IN OHMS
$1K = 10^3$ OHMS
ALL RESISTORS ½ WATT UNLESS OTHERWISE SPECIFIED

VOLTAGES MEASURED TO GROUND
CIRCUIT GROUNDS INSULATED FROM CHASSIS
ONE POWER SUPPLY USED FOR FOUR AMPLIFIERS

FIG. 36. REGULATED POWER SUPPLY FOR USE WITH MOBILE-LABORATORY AMPLIFIERS.

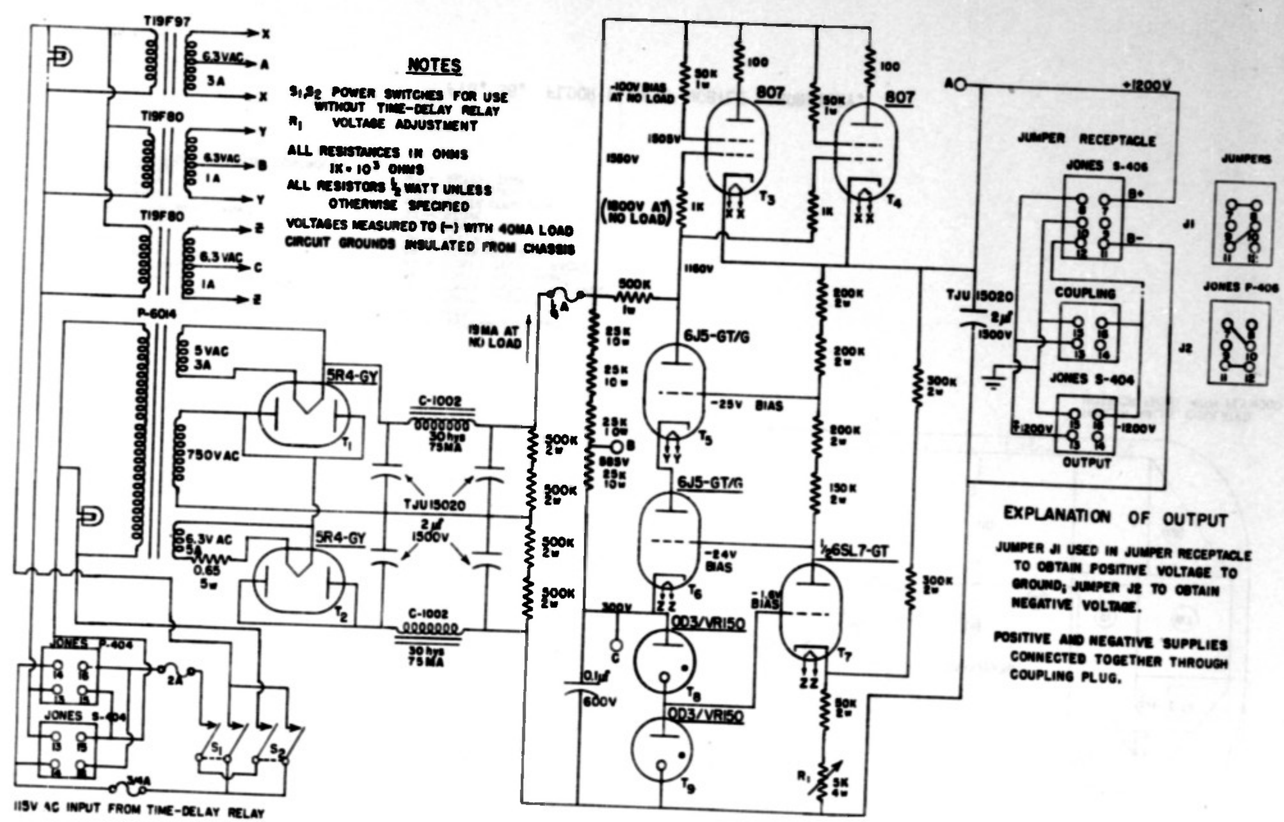
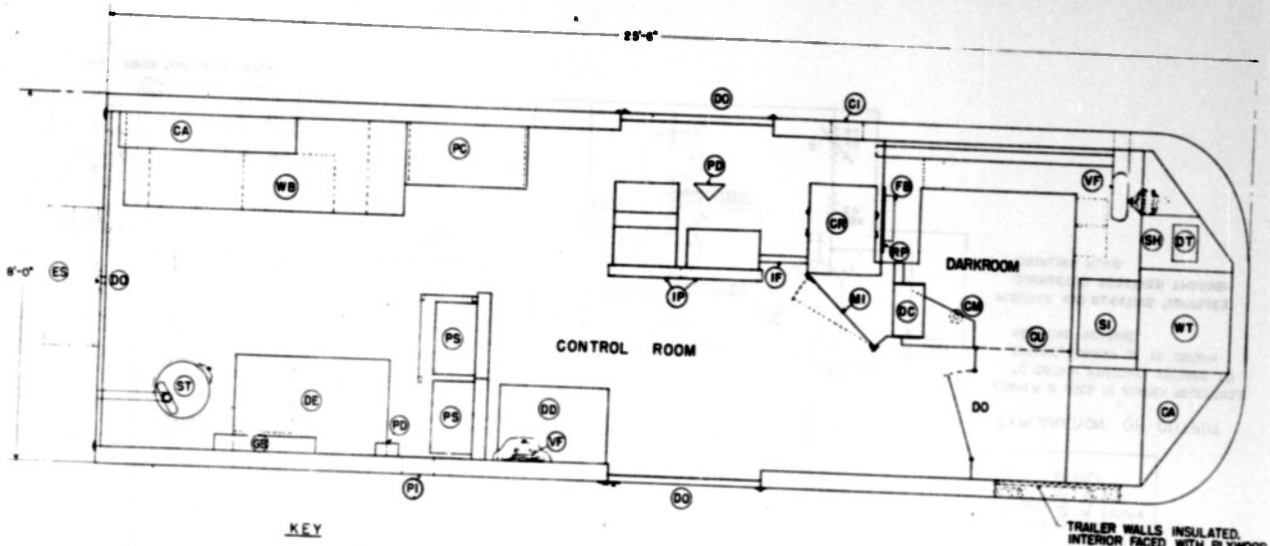


FIG. 37. HIGH-VOLTAGE POWER SUPPLY, REGULATED, FOR USE WITH CATHODE-RAY TUBES IN EIGHT-CHANNEL MOBILE LABORATORY.



KEY

CA - CABINET
CI - CABLE INPUT PANEL
CM - CAMERA MOTOR
CR - CATHODE-RAY TUBE RACK
CU - CURTAIN
DC - DRUM CAMERA
DD - DROP DESK
DE - DESK
DO - DOOR
DT - DEVELOPING TANKS
ES - ENTRANCE STAIRS
FB - FILM BOX
GB - GAUGE BOX
IF - INTENSITY AND FOCUS CONTROLS
IP - INSTRUMENT RACKS
MI - MIRRORS
PC - PARTS CABINET
PD - POWER DISTRIBUTION PANEL
PI - POWER INPUT PANEL
PS - POWER SUPPLY RACKS
RP - REMOVABLE PANEL
SH - SHELVES
SI - SINK
ST - STOVE
VF - VENTILATING FAN
WB - WORK BENCH
WT - WATER TANK

FIG. 38. FLOOR PLAN OF MOBILE LABORATORY.

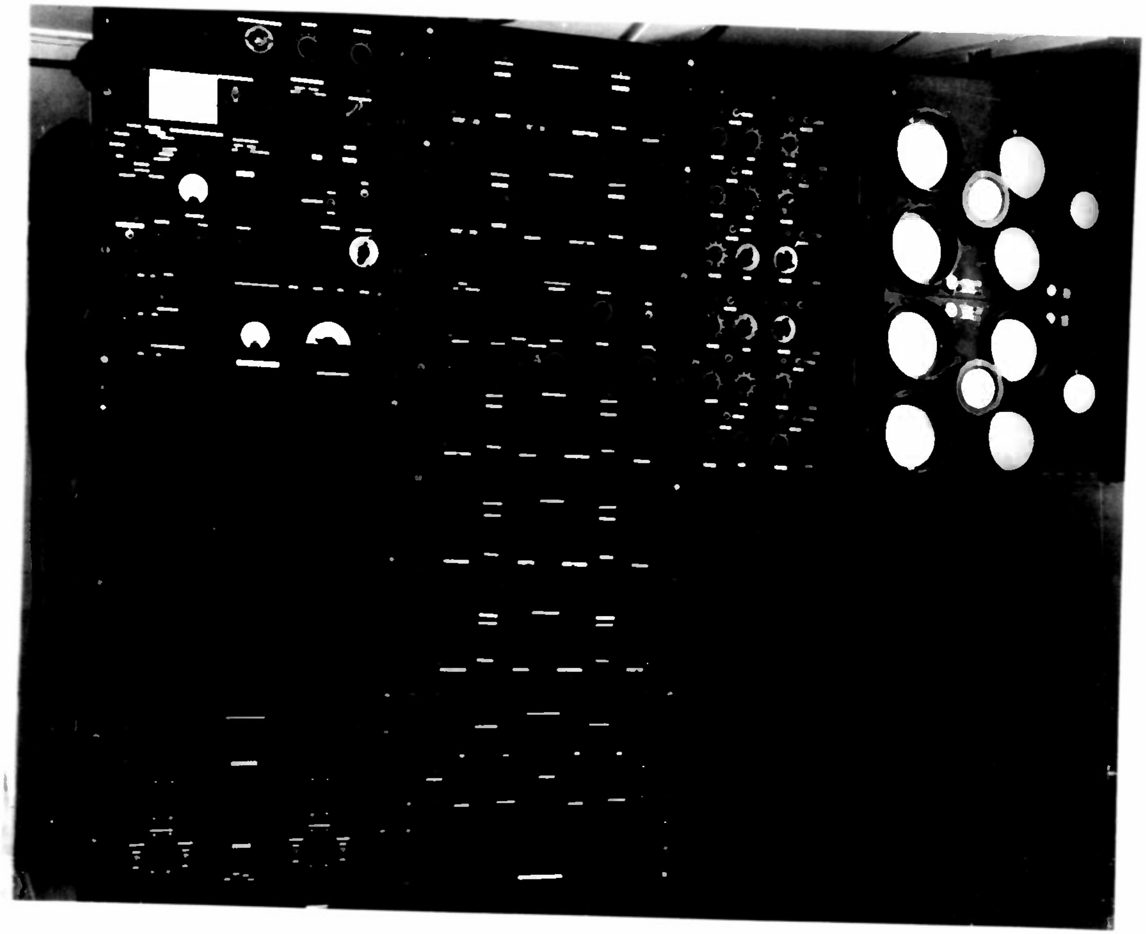


FIGURE 39. INSTRUMENT AND CATHODE-RAY TUBE RACKS IN MOBILE LABORATORY

FIGURE 40. POWER CONTROL AND INSTRUMENT RACKS IN MOBILE LABORATORY

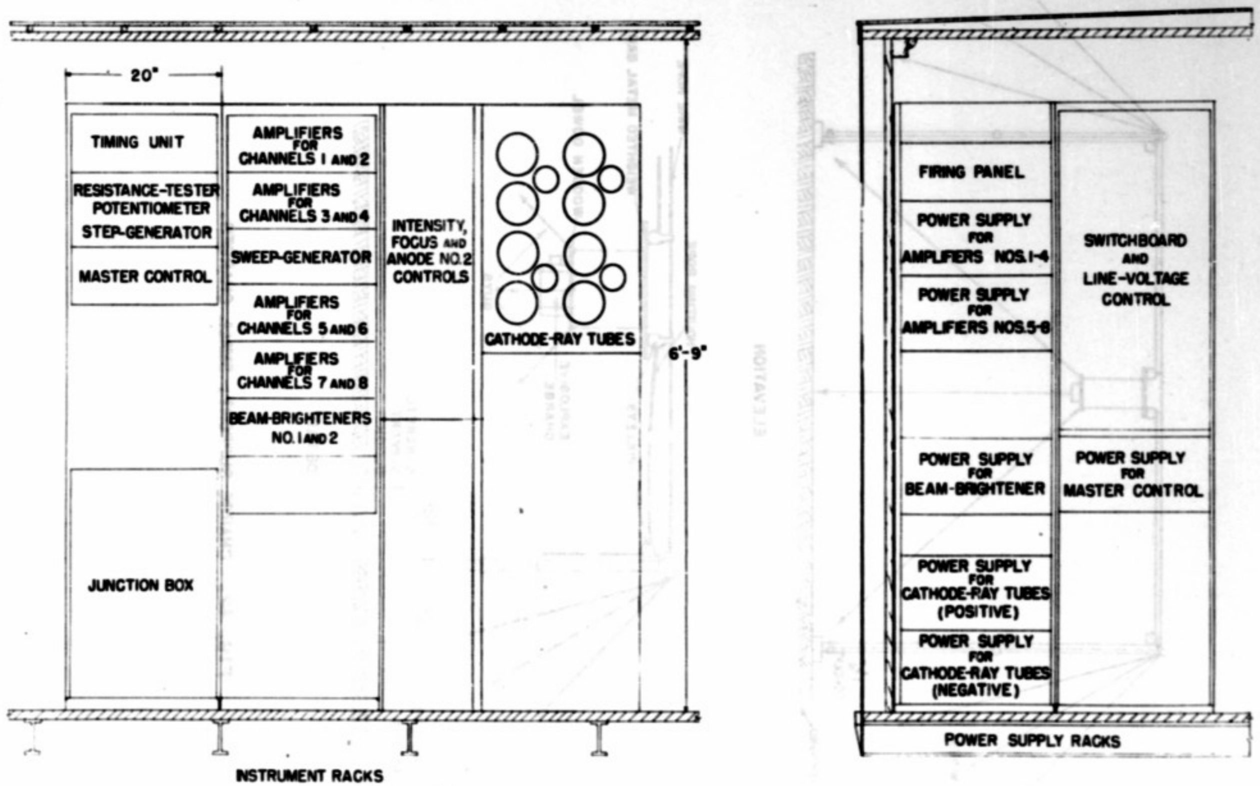


FIG. 41. ELEVATION OF ELECTRONIC EQUIPMENT IN MOBILE LABORATORY.

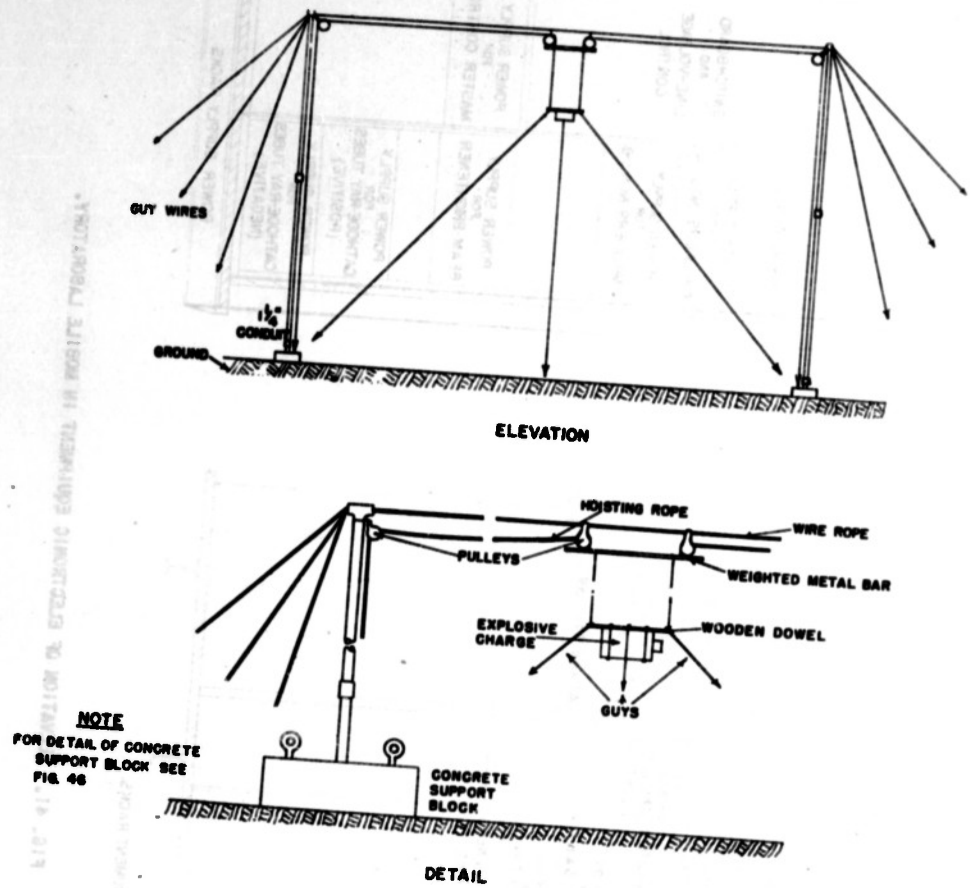


FIG. 42. CHARGE SUPPORT; SMALL CHARGES.

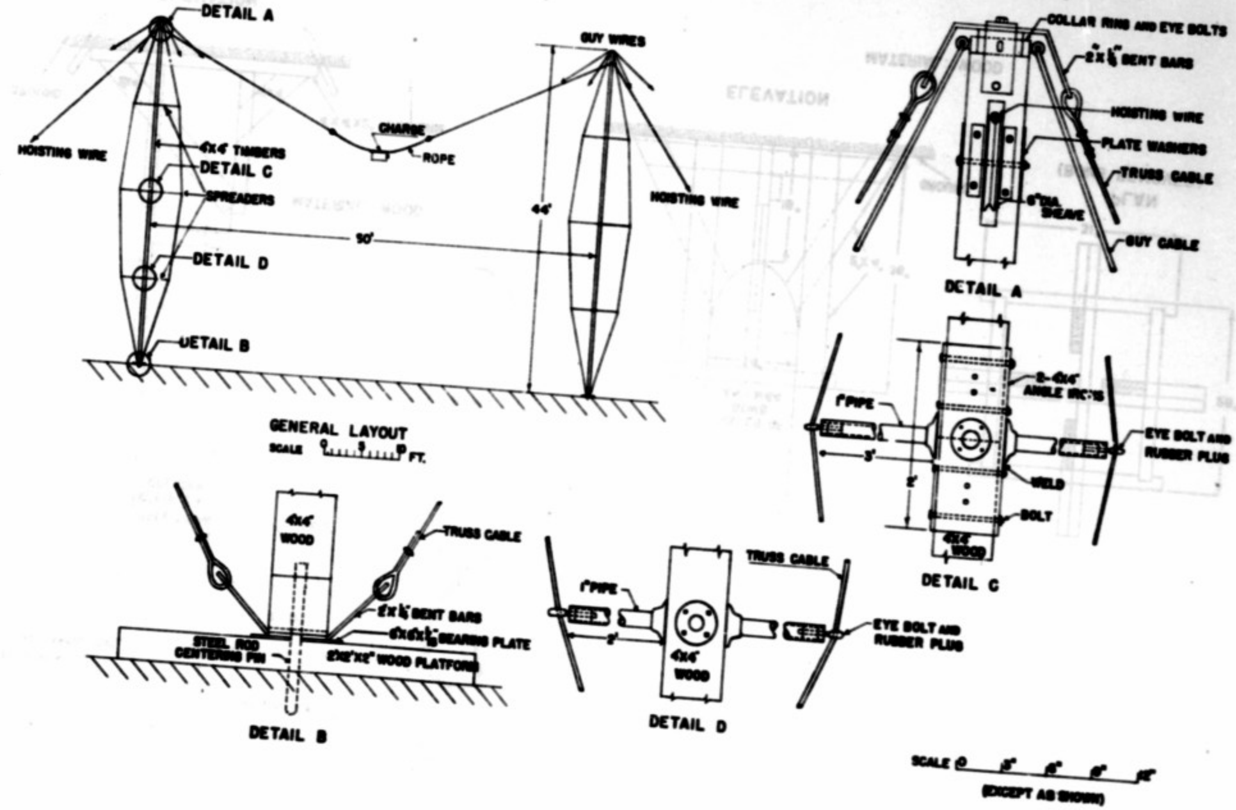


FIG. 43. CHARGE SUPPORT.

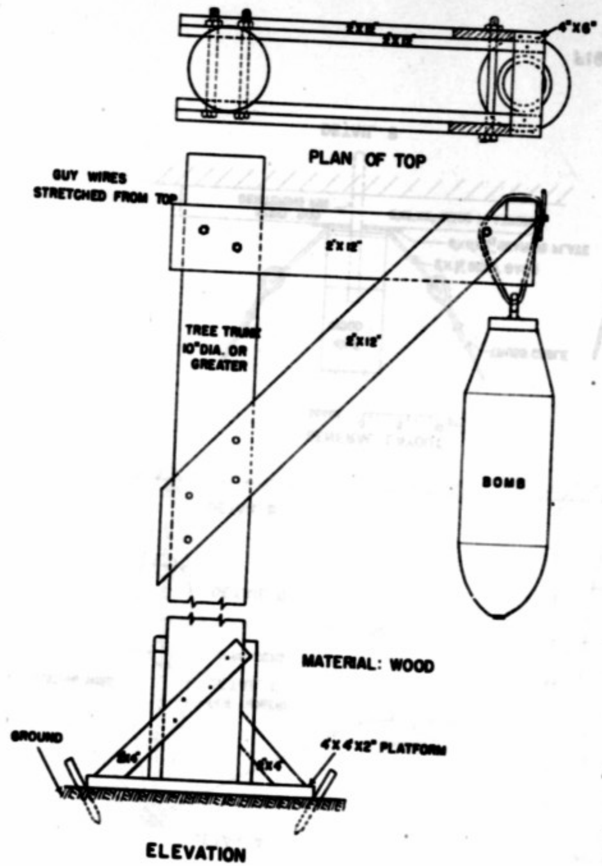


FIG. 44. BOMB SUPPORT; BOMB ELEVATED.

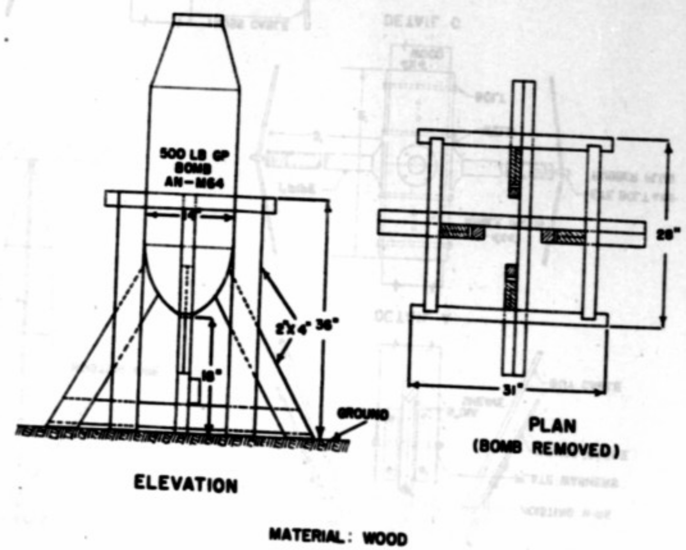


FIG. 45. BOMB SUPPORT; BOMB NEAR GROUND.

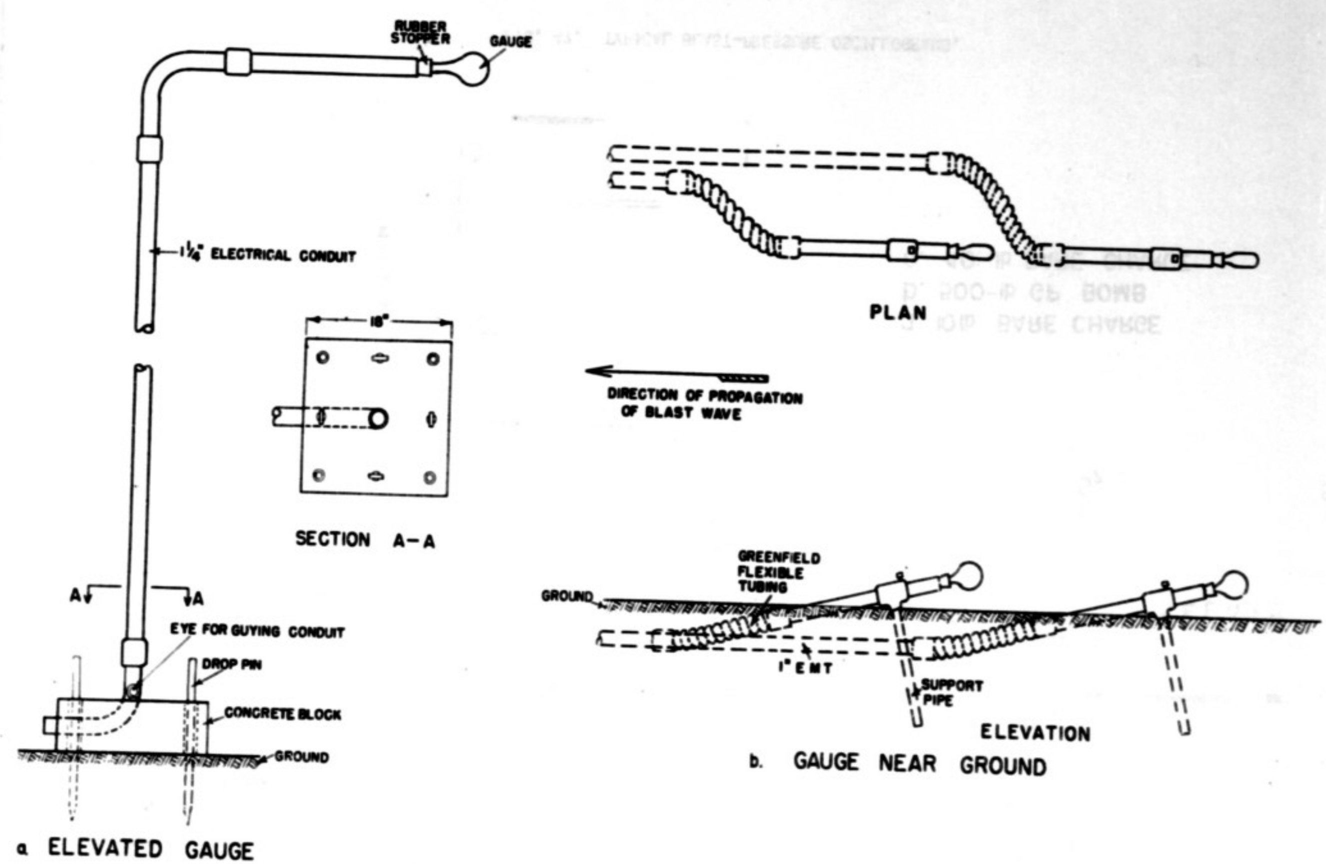


FIG. 46. GAUGE SUPPORTS.

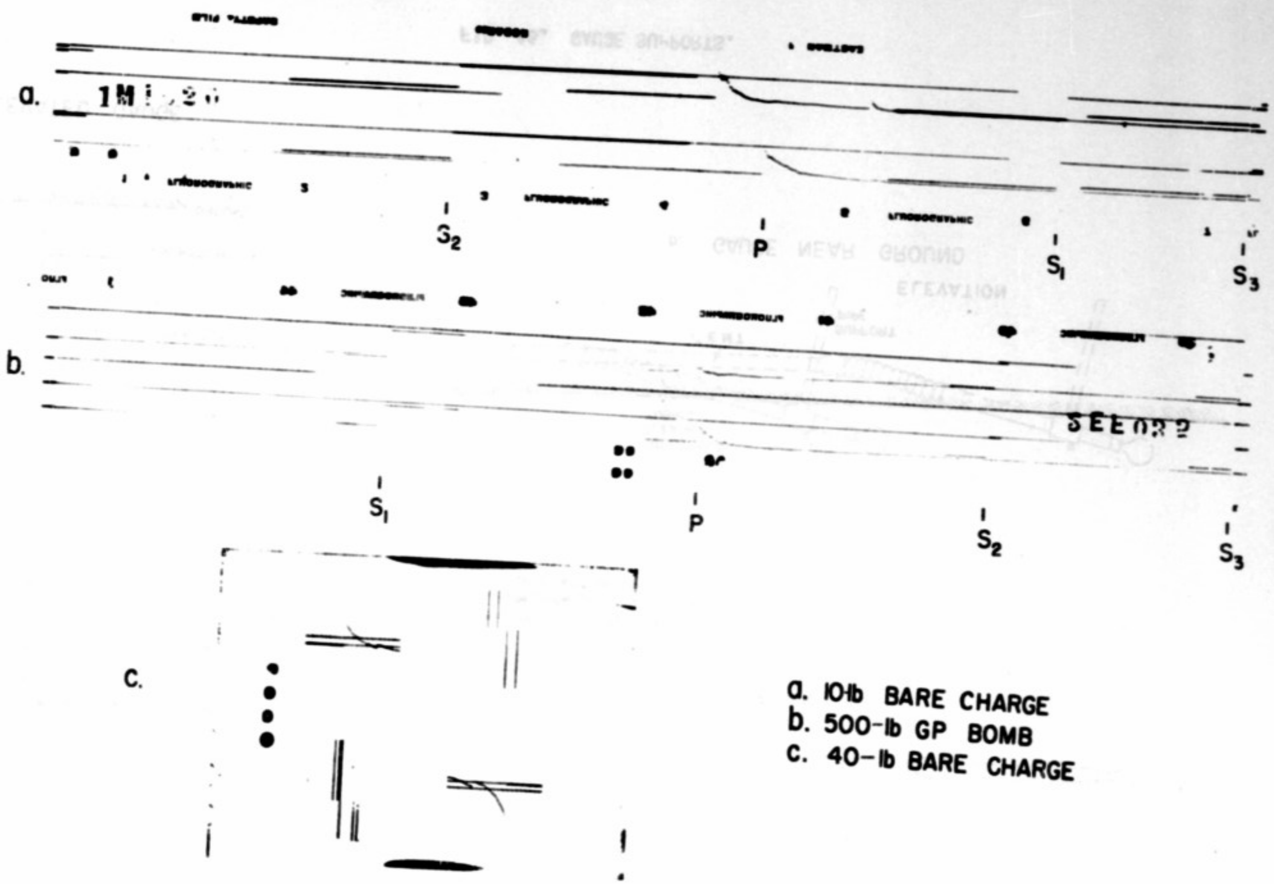
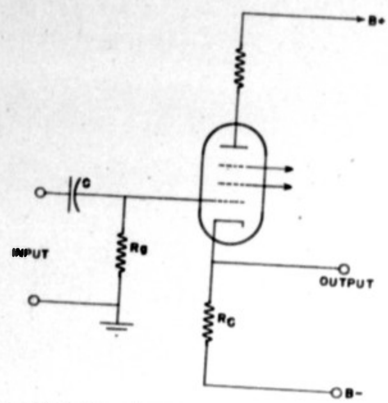
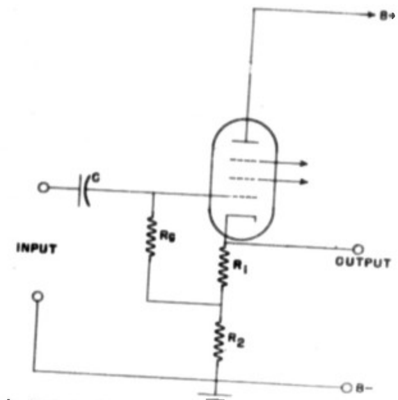


FIG. 47. TYPICAL BLAST-PRESSURE OSCILLOGRAMS.



a. LARGE GRID RESISTOR TYPE



b. SMALL GRID RESISTOR CATHODE-FOLLOWER TYPE

FIG. 48. HIGH-IMPEDANCE INPUT CIRCUITS.

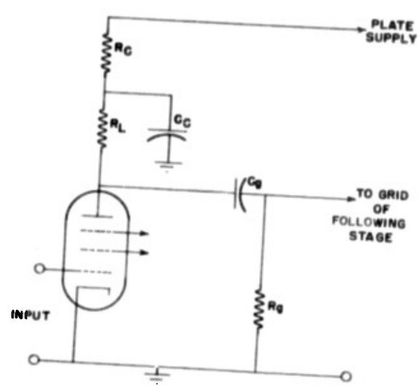


FIG. 49. LOW-FREQUENCY COMPENSATION.

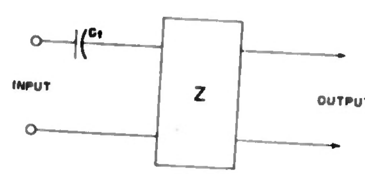


FIG. 50. CIRCUIT FOR MEASURING INPUT IMPEDANCE.

REEL – C

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A.T.I.

12584

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TITLE: Apparatus for the Measurement of Air-Blast Pressure by Means of Piezo-electric Gages

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Explosions - Shock and pressure measurement
Explosions - Blast waves - Calculations

p14/2

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ABSTRACT:

Description and requtrements are given of an apparatus used for measuring, by means of a ptezoelectrtc gage, peak pressure and posttive tmpulse in air blast from high explosives. Technique of measurtng shock-wave velocity, from which peak pressure may be calculated, is descrtbed. Applicatton of equation which relates pressure to veloctty ts discussed. Reproductions of typtcal oscillograms obtained with this apparatus are presented.

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